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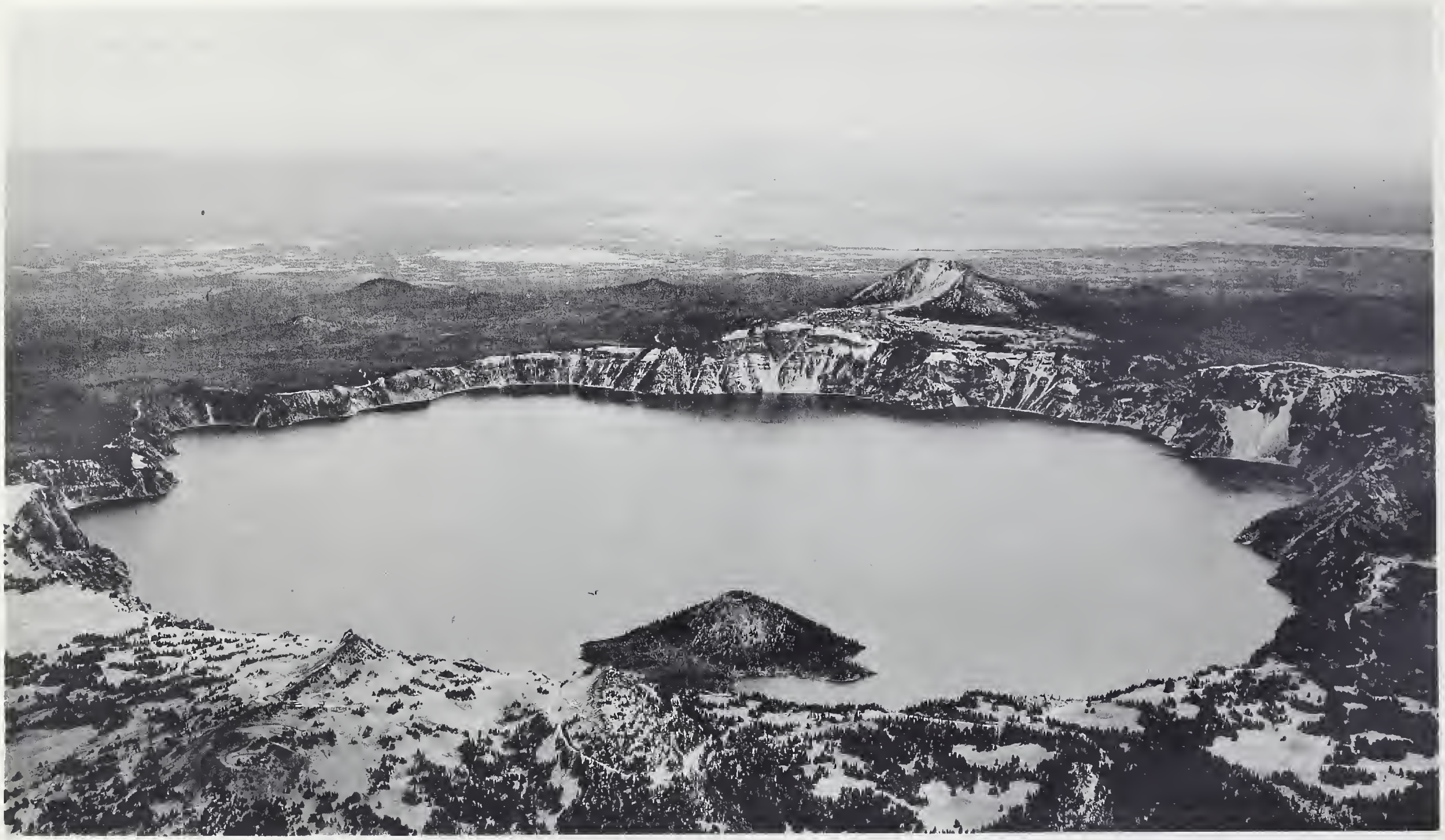

*Photograph by 116th Photo Section, Washington National Guard*

Crater Lake viewed from the west

The Watchman, one of the Northern Arc of Vents, rises on the caldera rim in front and to the left of Wizard Island. To the north (left) rises Hillman Peak, connected by a ridge with the parasitic cinder cone known as Forgotten Crater. Next to the left is the great dacite flow of Llao Rock. Continuing along the caldera rim, the white-topped cliff is Pumice Point, beyond which lies Cleetwood Cove, overlooked by the Cleetwood dacite flow. Farther on, where the caldera wall is low, are the thick andesite flows of the Palisades and Roundtop, which rest on glacial deposits. The conspicuous V-shaped cliff on the distant wall is formed by the Redcloud dacite flow; beyond it rises Mount Scott. The numerous hills on the outer slopes of Mount Mazama, behind Mount Scott, are parasitic domes of andesite and dacite. Still farther away is the interior plateau, thickly covered with the deposits of pumice flows (*nuées ardentes*).

# *The*
# Geology of Crater Lake National Park, Oregon

## *With a Reconnaissance of the Cascade Range Southward to Mount Shasta*

HOWEL WILLIAMS

CARNEGIE INSTITUTION OF WASHINGTON PUBLICATION 540
WASHINGTON, D. C.
1942

THE WILLIAM BYRD PRESS, INC., RICHMOND, VIRGINIA
THE MERIDEN GRAVURE COMPANY, MERIDEN, CONNECTICUT
THE VIRGINIA ENGRAVING COMPANY, RICHMOND, VIRGINIA

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# The Geology of Crater Lake National Park, Oregon

## *With a Reconnaissance of the Cascade Range Southward to Mount Shasta*

## ABSTRACT

IN LATE Cretaceous times, the site of the Oregon Cascades was largely if not entirely occupied by a shallow sea. During the Eocene period, widespread uplift drove the coast westward beyond the line of the Cascade Range, never to return. Volcanism began in eastern Washington during the early Eocene and gradually spread southward over Oregon. By late Eocene times, volcanoes were active throughout the present Cascade belt and on the plateau of central Oregon. The climate of Oregon was then warm temperate or subtropical, and a low plain spread far inland. During Oligocene and Miocene times, volcanism continued on a grand scale. Farther east, the volcanic deposits of the John Day formation had been laid down over an extensive area and had been buried during the Middle Miocene by enormous outpourings of Columbia River plateau basalt, erupted from swarms of fissures. Meanwhile the climate had become cooler and a temperate, redwood flora had replaced the warmer floras of the Eocene. Still, however, no high mountain range divided eastern from western Oregon.

At the end of the Miocene period, renewed earth movements took place. At the same time, the volcanics of the Western Cascades were intruded by an approximately north-south line of dioritic stocks. Simultaneously, north-south fractures opened along and near what is now the crest of the Cascade Range. An important effect of these disturbances was the elevation of a mountain barrier which shut off eastern Oregon from the supply of moisture-laden winds. For the first time, the floras on opposite sides of the Cascades began to show the marked differences which they exhibit today.

During the Pliocene period, the disturbed rocks of the Western Cascades suffered rapid erosion, and along the summit of the range they were buried by the products of High Cascade volcanoes. These volcanoes were less explosive than those which had formed the Western Cascade series, and their products were less diverse. Whereas the older lavas range from rhyolite to basalt, those of the High Cascade cones are almost entirely composed of olivine-bearing basaltic andesite and basalt. Many of these younger flows poured for long distances down canyons cut across the Western Cascades.

By the close of the Pliocene period, the crest of the Cascade Range had become a high plateau surmounted by overlapping shield-shaped cones of basic lava. In the succeeding Pleistocene period, a narrower, north-south belt of giant andesitic volcanoes commenced to form on the basaltic plateau. These continued to erupt and grow until Recent times. Today they form the crowning peaks of the Cascade Range. The bulk of this report deals with the rise of one of these andesitic cones, Mount Mazama, and the manner in which its summit was destroyed.

Mount Mazama rose from a basement the elevation of which lay between 5000 and 6000 feet. By the time the volcano reached full stature, the summit rose to a height of approximately 12,000 feet. The main cone was built chiefly by quiet effusions of hypersthene andesite. Explosive activity was relatively unimportant. Eruptions took place from a number of conduits, the positions of which changed from time to time. Accordingly, Mount Mazama was never a simple, symmetrical cone; it was, rather, a complex of overlapping cones.

Toward the close of the period of andesitic eruptions, flows of dacite escaped from fissures far down the south and east flanks of the volcano, and explosions of dacite pumice alternated with flows of andesite from the summit vents.

Perhaps from the beginning, Mount Mazama supported many glaciers. Even the oldest visible lavas are underlain by glacial moraines. In many places, the caldera cliffs reveal layers of bouldery till and fluvioglacial sand interbedded with volcanic rocks. The constructional forces building the volcano struggled incessantly with the erosive force of ice. Clearly, the glaciers advanced and retreated many times. Their greatest advance came after the dacitic eruptions mentioned above. At that time, many tongues of ice were more than 10 miles long, and one extended 17 miles from the summit. In some of the canyons, the thickness of the glaciers exceeded 1000 feet. Save for a few projecting arêtes, the whole of Mount Mazama was mantled by an uninterrupted sheet of ice.

After the period of maximum glaciation, when the ice had retreated from the divides and was confined to the canyon bottoms on the upper slopes of the volcano, a semicircular arc of vents opened on the north flank, approximately 5000 feet below the summit. From this Northern Arc of Vents, which determines the position of the north wall of Crater Lake, viscous flows of andesite and dacite were erupted. About the same time, a cluster of acid andesite and dacite domes rose near the east base of Mount Mazama, and many basaltic cinder cones were active on the lower slopes. Explosions of dacite pumice, partly in the form of glowing avalanches *(nuées ardentes),* also took place from the summit region.

A long period of quiescence ensued. The glaciers retreated until only three small tongues extended beyond what is now the rim of Crater Lake. Even the longest stretched less than a mile and a half beyond the caldera rim. The slopes of the volcano were almost barren of vegetation.

The climactic eruptions then began. At first they were mild, but soon they increased in violence. During the initial stages, fine dacite pumice was blown high above the summit vents, to be drifted eastward by the wind. As the explosions became more violent and the pumice lumps increased in size, the wind veered toward the northeast. No less than 5000 square miles were buried beneath the ejecta to a depth of more than 6 inches. The finer dust spread over a vastly larger area. So much pressure was thus released that the gases in the feeding magma escaped from solution with unusual rapidity. The pumice was no longer projected high above the vents, but escaped in prodigious amount, boiling over the crater rims and rushing down the sides of the volcano at a tremendous rate, flowing after the manner of glowing avalanches. Most of this pumice was confined to the canyons, down which it raced for distances up to 35 miles. Where no canyons existed, the pumice flows spread as incandescent sheets. Those that swept down the east and northeast sides of the volcano deployed onto the flats bordering the Klamath Marsh. Such was their power that they traveled 25 miles from their source, though half their journey lay across a plateau. Twenty miles from the vents, the flows include bombs of pumice 14 feet across. Just before the glowing avalanches ceased, the ejecta changed from dacite pumice to crystal-rich basic scoria. When the eruptions had come to an end, the glacial canyons were transformed into broad plains dotted with countless fumaroles. Each canyon had become a "Valley of Ten Thousand Smokes." The abundance of charred logs within the deposits offers vivid testimony to the destruction of the forests.

When the culminating eruptions were over, the summit of Mount Mazama had disappeared. In its place, there was a caldera between 5 and 6 miles wide and 4000 feet deep. How was this formed? Certainly not by the explosive decapitation of the volcano. Of the 17 cubic miles of solid rock that vanished, only about a tenth can be found among the ejecta. The remainder of the ejecta came from the magma chamber. The volume of the pumice fall which preceded the pumice flows amounts to approximately 3.5 cubic miles. Only 4 per cent of this consists of old rock fragments; 10 to 15 per cent consists of crystals, and the rest is made up of pumiceous glass. The volume of the pumice flows is approximately 8 cubic miles. Of this amount, only 15 to 20 per cent consists of old lava fragments. The remainder represents new magma in the form of crystals and glass. Weak, dying explosions deposited approximately a quarter of a cubic mile of fine ejecta, chiefly crystals and minute chips of rock. Accordingly, 11.75 cubic miles of ejecta were laid down during these short-lived eruptions. In part, it was the rapid evacuation of this material that withdrew support from beneath the summit of the volcano and thus led to profound engulfment. The collapse was probably as cataclysmic as that which produced the caldera of Krakatau in 1883.

Some process other than the expulsion of magma from the feeding chamber must also have operated. Whereas 17 cubic miles of the volcano disappeared, at most 11.75 cubic miles of ejecta were laid down. Moreover, by far the bulk of these ejecta consists of vesicular glass. The equivalent volume of liquid magma was less than half as much. Accordingly, it must be concluded that during or immediately before the great eruptions, large volumes of magma were injected into fissures at depth. It was by a combination of deep-seated intrusion and explosive eruption that the magma chamber was drained to make room for the collapse of the peak of Mount Mazama. Doubtless the caldera floor also subsided by cooling and solidification of the magma left below.

The collapse of Mount Mazama was eccentric with respect to the former summit, for this lay well to the south of what is now the center of Crater Lake. This eccentric collapse was controlled by the pre-existing semicircular line of weakness along which the Northern Arc of Vents was formed.

The formation of Crater Lake took place approximately 5000 years ago. The discovery of artifacts beneath the pumice deposits shows that man already inhabited this part of Oregon and was a distant witness of the catastrophe.

After a period of quiet of unknown duration, activity commenced anew. Close to the western edge of the caldera rose the cone of Wizard Island, the final act of which was to erupt a rugged sheet of blocky lava, perhaps no more than a thousand years ago. As intra-caldera eruptions went on, rain and snow formed a lake on the floor, and this continued to gain in volume until it reached a depth of almost 2000 feet.

# Introduction

Crater Lake National Park lies on the crest of the Cascade Range in southern Oregon, in the heart of the great volcanic province of the Pacific Northwest. No matter from which direction the traveler approaches, at least the last sixty miles of his journey are over volcanic rocks. Within the park, the road climbs steadily, mile after mile up the flanks of an old volcano until it brings him with breath-taking suddenness to the very brink of the precipitous walls that encircle Crater Lake. The scene is one of overwhelming beauty. Twenty miles of cliffs, delicately tinted in shades of gray, pink, purple, orange, and brown, enclose a circular body of water unexcelled in the rich depth of its blueness. The thoughtful visitor cannot remain long on the edge of this vast depression without asking himself how it came to be. He cannot doubt that the lake lies within an extinct volcano, for on all sides the lavas and fragmental deposits dip outward; nor can he doubt that the summit of the original cone rose far above its present ruins. How else can he explain those great U-shaped glacial valleys beheaded by the caldera walls? Surely glaciers powerful enough to carve such valleys must have had their source on a vanished peak. This much is clear from a cursory study. Somehow this ancestral, ice-clad peak disappeared, leaving in its place a giant depression more than 5 miles wide and 4000 feet deep. Shortly thereafter new eruptions began on the floor of the caldera, and rain and melting snows covered it with water. The scene of desolation left by the catastrophe slowly took on its present grandeur.

In order to appreciate most clearly the relation of Crater Lake to the neighboring volcanoes of the Cascade Range, the visitor should climb to the top of the Watchman, a peak on the western rim, or, better, to the summit of Mount Scott, which rises a short distance to the east of the rim. From either vantage point, he is sure to be impressed by the fact that Crater Lake does indeed occupy a basin in the summit of a decapitated volcano, and, giving fancy sway, he may picture the remnant slopes sweeping upward to a peak a mile above the crater rim. To this imaginary peak others have given the name Mount Mazama.

In a rough way, the panorama from the summit of the Watchman or Mount Scott may be separated into four parts, distinct both topographically and geologically. Recognition of these units is fundamental to an understanding of the history of the region.

There is, first, a north-south belt, generally between 20 and 25 miles wide, that passes through Crater Lake. This belt, known as the High Cascades, consists of Pliocene and younger volcanic cones. Here the typical slopes are constructional. To this belt belongs the chain of majestic cones that extends from Lassen Peak in the south to Mount Baker in the north, 500 miles removed. To it belong Mounts Shasta, McLoughlin, and Thielsen, the Three Sisters, Mounts Hood, St. Helens, Adams, Rainier, and Baker, and a host of lesser peaks.

West of the High Cascades lies a second belt, parallel and slightly wider, composed of older volcanic rocks ranging in age from Eocene to Upper Miocene. It is customary to speak of this belt as the Western Cascades. Here the conical peaks characteristic of the High Cascades are conspicuous by their absence; here there are no original volcanic slopes. Westward-flowing rivers with headwaters among the High Cascades, such as the Rogue and the Umpqua, have cut deep canyons across the gently folded rocks of the Western Cascades, and subsequent tributaries have carved broad north-south valleys along the strike. In contrast with the youthful topography of the High Cascades, the topography here is mature or submature. It is a region of narrow-crested, winding ridges. By reason of these contrasts, the accustomed eye has no difficulty in following from afar the boundary between the two belts.

Beyond the Western Cascades, on the distant sky line, rise the rugged peaks of a third region, the Klamath-Siskiyou Mountains, composed for the most part of Jurassic and older schists intruded by large bodies of igneous rock ranging in character from serpentine to granite. This metamorphic and igneous series makes up the so-called "bedrock complex" beneath the Western and High Cascades. Undoubtedly such rocks pass beneath Crater Lake, for they reappear from below the Tertiary volcanic cover in eastern Oregon. Since Cretaceous time, all but the fringe of the Klamath-Siskiyou Mountains have remained above the sea, and though suffering erosion throughout that period, the mountains have continued to rise.

The topographic contrasts between the three provinces just described, striking as they are, seem small in comparison with that which distinguishes the fourth, for when the observer turns eastward, away from the "sea of peaks and ridges," he looks on an immense plateau of basalt, relieved here and there by steep-scarped, tilted fault-block mountains. This is the Interior Platform, which stretches northward into Washington and eastward, beyond the range of vision, into Idaho. Much of its surface is composed of Pliocene basalt, but where the plateau is entrenched by deep box canyons the older, gently folded Tertiary volcanic rocks are exposed. These pass beneath the High Cascade lavas and interfinger with the volcanic deposits of the Western Cascades.

## Suggested Excursions

It may be helpful to the visiting geologist to mention the features of particular interest that he should see according to the length of time at his disposal. If his stay be brief, he should devote it chiefly to examination of the caldera walls, for nowhere can he gain a clearer picture of the internal structure of a volcano. Most calderas of comparable size are so deeply eroded or so masked by vegetation that their structure is difficult to decipher, but here the precipitous walls are bare and rise 2000 feet above the lake, revealing with singular clarity the manner in which the volcano was built. The visitor with only a day to spare should either drive around the caldera on the Rim Road, or, preferably, take the morning boat trip which encircles the lake close to the base of the cliffs. Should he take the trip by boat, he will find it pleasant and instructive to devote the afternoon to an excursion on Wizard Island, where he may examine the cinder cone and rugged lava field at its foot, products of the final eruptions within the park. If, on the other hand, he chooses the drive along the Rim Road, he should allow sufficient time to climb both the Watchman and Mount Scott, in order to gain a clearer picture of the geological setting of Crater Lake.

The walls of the caldera are unquestionably the most important feature of the park from a geological point of view. Perhaps next in interest are the pumice- and scoria-filled canyons in the southern part of the park. Fortunately the highway from the eastern entrance follows the rim of Sand Creek canyon and provides many unobstructed views of the fantastically eroded fragmental deposits and of the "fossil fumaroles" which occur among them. The highway from the southern entrance follows the rim of Annie Creek canyon and affords similar views. If time permits, it is well worth while to examine the canyon walls from top to bottom, either at Godfrey's Glen near Annie Spring or at the Pinnacles on Sand Creek.

Both the caldera walls and the pumice-filled canyons can be seen in a single day, but several days may be profitably devoted to more detailed examination of each. The only official trail down the caldera wall leads to the boat landing on the south side of the lake. Unfortunately, the descent here reveals less of interest than almost any other part of the entire circumference. In fact there is little of particular interest on the south wall of the caldera that cannot be seen adequately from a boat. But the north wall, from the Watchman to Redcloud Cliff, displays a wide variety of volcanic and glacial features deserving close inspection. Here may be seen the feeders of the dacite flows of Llao Rock, Cleetwood Cove, and Redcloud Cliff, and abundant dikes, including the Devil's Backbone. For those interested in seeing moraines and fluvioglacial deposits interbedded with lavas, there are no better places than beneath the Roundtop and Palisade flows and along the southern side of Cloudcap Bay. Almost all the features just mentioned may be examined without difficulty or danger; some, however, are accessible only to one with a stout pair of climbing shoes and a steady head.

Next to an exploration of the walls of the pumice-filled canyons, perhaps the most interesting trip outside the caldera is to the summit of the Union Peak volcano. A motor road leads across the flanks of the glaciated lava shield to the base of the tuff cone inside the central crater and to the plug which fills the central conduit. Other trips may be made to the parasitic cinder cones on the slopes of Mount Mazama, though these show little that cannot be seen to better advantage on Wizard Island.

### Acknowledgments

The field and laboratory work on which this report is based has occupied the larger part of five years, from 1936 to 1940. My difficulty now is that the list of obligations has grown too large to enumerate. I must therefore mention only those to whom I am especially indebted. First among these is Dr. John C. Merriam, President Emeritus of the Carnegie Institution of Washington. It was at his request that the work was undertaken as part of his program for the scientific study of our national parks. To him I owe thanks, not only for constant interest and encouragement, but for generous funds which he placed at my disposal through the National Academy of Sciences. These funds defrayed most of the field expenses, the cost of many chemical analyses, and that of drilling four deep wells. Indirectly, I have also been assisted by Dr. Merriam's guidance of cooperative research on the geological and anthropological problems of southern Oregon. In this connection, I have benefited particularly by the work of Professor L. S. Cressman, of the University of Oregon, whose discovery of human artifacts beneath the ejecta of Mount Mazama first showed that when Crater Lake was formed man already occupied the neighboring country.

It is a pleasure also to record thanks to the superintendents of Crater Lake National Park, first Mr. David Canfield and later Mr. E. P. Leavitt, for many courtesies; to Mr. John E. Doerr, Jr., park naturalist, who took charge of the detailed re-sounding of Crater Lake; and to his assistants on the naturalist staff, notably Messrs. Wayne E. Kartchner and Loren Miller, who accompanied me in the field on several occasions and helped by reporting their own observations. During the season of 1938 Mr. Randall Brown, and during the next season Mr. Roy Turner, acted ably as field assistants.

In the matter of photographs, I wish to thank Messrs. Elmer Aldrich, William Schoeb, Victor Duran, and H. B. Taylor, the United States Army Air Corps, the Washington National Guard, and the National Park Service. The beautiful paintings reproduced as plate 18, figures 1 and 2, and plate 22, figure 2 were made under my direction by Mr. Paul Rockwood, of the National Park Laboratories, Western Division, at Emeryville, California. Mr. A. W. Severy, of the same laboratories, prepared certain of the maps; Dr. Henry P. Hansen made pollen analyses of peat samples from Munson Valley; Mr. W. H. Kirkbride, chief engineer of the Southern Pacific Company, placed at my disposal logs of wells drilled through the pumice deposits east of Crater Lake; my colleague Professor C. A. Anderson assisted by much profitable discussion; and, finally, the Board of Research of the University of California granted additional financial aid for transportation and chemical analyses.

# Discovery and Early Exploration

Crater Lake was discovered on June 12, 1853, by J. W. Hillman at the head of a party of prospectors from Jacksonville, Oregon. The discovery failed to arouse the attention it deserved, for in those days the interest of the western pioneers was concentrated on the search for gold and on the Indian wars. In 1862, and again in 1865, the lake was "rediscovered" independently by others.[1] Yet as late as 1872, when W. G. Steel arrived in Oregon, there were few who had ever heard of the lake, and it took him well-nigh ten years to find a single person who had actually been there. When, in 1885, Steel found an opportunity to visit the lake, he was so profoundly impressed by its beauty that he set himself steadfastly to the task of making it more widely known and having it established as a national park. In 1886, largely because of his efforts, President Cleveland issued an order withdrawing from settlement and sale ten townships surrounding and including Crater Lake, and in 1893 these were included in the Cascade Range Forest Reserve. Finally, after seventeen years, Steel achieved his object. In 1902, by an act of Congress, the lake and its immediate surroundings, totaling some 250 square miles, were set aside for the public use as a national park.

It was largely because of Steel's insistence that the first scientific survey was made. In 1885, he accompanied Major C. E. Dutton and Professor Joseph Le Conte to the lake, and in the following year Dutton returned with a party from the United States Geological Survey. A special map of the lake and its environs was made by M. B. Kerr and Eugene Ricksecker, and 168 soundings were made, among them one of almost 2000 feet. It was an astonishing find, and aroused widespread interest.

Dutton had previously spent much time in the Hawaiian Islands and was familiar with the large calderas of Kilauea and Mauna Loa. His opinion concerning the origin of Crater Lake therefore carried great weight. His was indeed the first scientific attempt to solve the problem. In a letter addressed to Powell, then director of the Geological Survey, he wrote:

> As regards the origin of the basin, I now have a decided opinion. It has, I think, been formed in much the same way as the great calderas of the Hawaiian Islands, by the melting of the foundations of the original mountains, the blowing out of the molten material in the form of light pumice and fine tufa. It cannot have been formed by an explosion, like Krakatoa and Tomboro, for there is no trace of the fragments anywhere in the country roundabout. But the pumice and tufa which surely emanated from the crater are seen in vast quantities anywhere within a radius of 20 to 60 miles, and in quantities ample to fill the whole vast crater twice over. The age of the crater is wholly post-glacial. I have found at the extreme crest of the wall on the western side splendid examples of glacial striation while the old moraines are half a mile to a mile below. That the age of the caldera cannot be great is evident from the fact that though the walls are crumbling at a very rapid rate the talus has not only failed to reach the water surface anywhere, but the sounding discloses little of it at the bottom.[2]

More than half a century has passed since Dutton put forward this hypothesis. Since then radically different hypotheses have been suggested. Yet the present survey has shown that Dutton was essentially correct, not only as to the origin, but also as to the age of Crater Lake.

The main task of studying the region in detail, Dutton left to his associate on the Geological Survey, J. S. Diller. Diller had visited Crater Lake as early as 1883, in company with Everett Hayden, and had spent several days exploring parts of the rim and Wizard Island. Between 1883 and 1886, he had been engaged in a study of the Lassen Peak district and had made reconnaissance trips to many other volcanoes in the southern Cascades. He was therefore especially well qualified to undertake the survey of Crater Lake. His first published accounts appeared in 1897, but his final report, supplemented by petrographic descriptions of the rocks by H. B. Patton, did not appear until 1902.[3] It was a splendid piece of work, all the more to be praised when we recall how he was hampered by lack of time, by difficulties of access, and by the scarcity of suitable places to camp.

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[1] For a résumé of the early exploration, see M. W. Gorman, "The discovery and early history of Crater Lake," Mazama, vol. 1, no. 2, pp. 150–161, 1897.

[2] The Oregonian (Portland), September 6, 1886. See also Eighth Ann. Rept., U. S. Geol. Surv., pt. 1 (1886–1887), pp. 156–159, 1889; "Crater Lake, a proposed national park," Science, vol. 7, pp. 179–182, 1886.

It would occupy too much space here to review Diller's findings in full; many of them are referred to below. His main conclusion concerning the origin of Crater Lake should, however, be emphasized. Like Dutton, he could not subscribe to the view that explosion by itself was the cause. He realized that in order to feed the powerful glaciers which once spread down the sides of the old volcano, the summit must have been far higher than the present rim of the caldera, and he supposed that it may even have exceeded 14,000 feet in height. Approximately 17 cubic miles of material must therefore have disappeared to form the caldera. But if this volume of rock had simply been removed by explosion, a tremendous layer of debris should be found close to the rim. No such layer was to be seen. Accordingly he concluded that the top of the old volcano must have been engulfed. He supposed that engulfment was brought about, as in the case of the calderas of Hawaii, by withdrawal of support from beneath the top of the volcano following copious eruptions of lava far down the flanks, and though he searched in vain for the products of such eruptions, he did not despair that some day they would be found.

More than thirty years elapsed before the next important contribution was made to an understanding of the geology of Crater Lake. In 1934, B. N. Moore[4] published an account of the great pumice sheet that encircles the lake. He was the first to recognize the dual character of the pumice deposits. One type is heavily charged with large lumps, is typically unsorted, and contains many charred logs. This type he realized to be the product of glowing avalanches or *nuées ardentes* like those erupted from Mount Pelée during the devastating activity of 1902. The other type of pumice is spread over hill and valley as a continuous mantle. This deposit is far more extensive, covering an area of more than 5000 square miles. It is granular and well sorted, and with increasing distance from the lake it becomes thinner. Clearly this pumice was ejected high above the volcano and was drifted northeastward by the prevailing winds, to fall in showers along the path.

Another notable advance in the interpretation of Crater Lake was made by W. W. Atwood, Jr.,[5] who in 1935 published the results of glacial studies commenced four years earlier. Atwood was the first to realize that during the slow growth of the volcano glaciers repeatedly advanced and retreated on its flanks. He revealed the story of a long struggle between the erosional and constructional processes that shaped the ancestral Mount Mazama.

In 1936, J. E. Allen[6] examined the internal structure of the dacite flows of Llao Rock, Grouse Hill, and Cleetwood Cove, and determined the manner of extrusion. At the same time he proved that the Cleetwood lava, which extends from the caldera rim to the water's edge, is not really a "backflow," as Diller had supposed, but is the filling of an inclined feeder laid bare by the collapse of Mount Mazama.

Finally, in the same year, W. D. Smith and C. R. Swartzlow[7] cast doubt on the idea that Crater Lake was formed by engulfment. On the basis of evidence offered by new exposures, they maintained that Diller had been misled concerning the volume of coarse ejecta around the rim. In their opinion, there seemed ample fragmental material to account for the formation of the caldera by devastating explosions. They thought that much of the shattered top of the volcano was blown far beyond the confines of the park, that much lies concealed beneath the ubiquitous mantle of pumice, and that much has been removed by erosion; and it appeared to them that the shape of the caldera itself was indicative of explosion. The challenge of their conclusions fostered new interest in the problem of Crater Lake.

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[3] J. S. Diller, "Crater Lake, Oregon," Nat. Geogr. Mag., vol. 8, pp. 33–48, 1897; reprinted in Ann. Rept. Smithsonian Inst. for 1897, pp. 369–373, 1898. J. S. Diller and H. B. Patton, "The geology and petrography of Crater Lake National Park," U. S. Geol. Surv. Prof. Paper 3, 1902.

[4] B. N. Moore, "Deposits of possible *nuée ardente* origin in the Crater Lake region, Oregon," Jour. Geol., vol. 42, pp. 358–385, 1934. See also "Nonmetallic mineral resources of eastern Oregon," U. S. Geol. Surv. Bull. 875, pp. 155–166, 1937.

[5] W. W. Atwood, Jr., "The glacial history of an extinct volcano, Crater Lake National Park," Jour. Geol., vol. 43, pp. 142–168, 1935. See also "Crater Lake and Yosemite through the ages," Nat. Geogr. Mag., vol. 72, pp. 327–341, 1937.

[6] J. E. Allen, "Structures in the dacitic flows at Crater Lake, Oregon," Jour. Geol., vol. 44, pp. 737–744, 1936.

[7] W. D. Smith and C. R. Swartzlow, "Mount Mazama: explosion versus collapse," Bull. Geol. Soc. Amer., vol. 47, pp. 1809–1830, 1936.

Such, in brief, had been the progress of research when the present survey was begun, in 1936. The main objects of this survey were to determine the age and origin of the caldera. To accomplish these ends, it seemed desirable to reconnoiter a wide area surrounding the park in order to appreciate its geological setting with respect to neighboring volcanoes and to discover the nature of the basement beneath Crater Lake. Work begun ten years earlier among the volcanoes of the Lassen Peak region and on Mount Shasta was therefore continued northward into Oregon to connect with the survey of Mounts Thielsen and Bailey made in 1932. In this way a general picture was obtained of the structure and volcanic sequence of the southern Cascades over a distance of more than 100 miles. It seemed desirable also to examine other calderas for the light they might throw on the mode of formation of Crater Lake. With this in mind, a study was made of the large volcanic depressions of New Zealand, of the Javanese calderas, including Krakatau, Tengger, and Idjen, and of several calderas in Japan, particularly those of Aso, Towada, and Toya. The question of how Crater Lake was formed was then approached with greater confidence.

The present report deals chiefly with the results of field work and only secondarily with the microscopic petrography of the rocks, a subject of which Patton has already presented an admirable account in his contribution to Diller's monograph.

# The Foundations of Mount Mazama

## THE PRE-CRETACEOUS BEDROCKS

THE pre-Cretaceous formations of southwestern Oregon and northern California, collectively referred to as the "bedrock series," consist of a wide variety of metamorphic rocks, chiefly mica schists, metavolcanics, argillites, and quartzites, that were intruded during the late Jurassic by a complex of igneous rocks ranging in composition from granite to serpentine. These bedrocks form the rugged Klamath and Siskiyou mountains to the west of the Cascade Range. From Weed, at the foot of Mount Shasta, northward to Medford, the Pacific Highway follows the depression separating the Cascades from this bedrock province. From Medford north to Roseburg, the highway leaves the border zone and makes its circuitous way across the bedrock mountains, leaving the Cascades far to the east (see map, plate 2).

Although not a single fragment of bedrock has ever been found among the ejecta blown out by the volcanoes of the southern Cascades, rocks similar to those of the Klamath and Siskiyou mountains must underlie the Cascade Range, for in the Blue Mountains and elsewhere in eastern Oregon such rocks reappear from beneath the cover of younger deposits.

## CRETACEOUS FORMATIONS

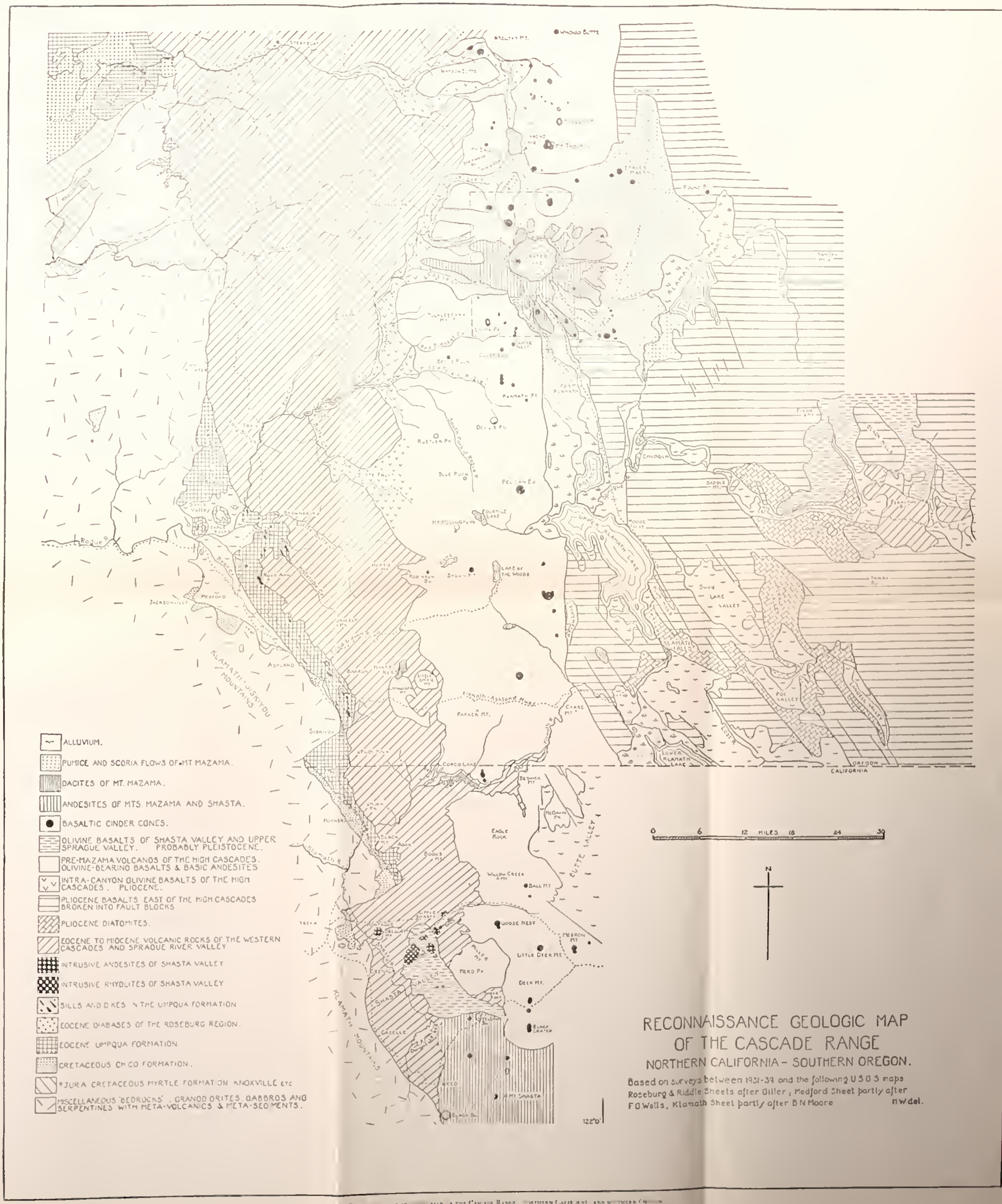
During much of late Cretaceous time, the present site of the southern Cascades was largely if not entirely occupied by a shallow sea extending at least as far east as the John Day Basin. In the Roseburg region, a thick series of Cretaceous rocks rests on a surface of moderate relief cut in the plutonic and metamorphic bedrocks. These Cretaceous rocks approach within 40 miles of Crater Lake, where they dip beneath the Tertiary volcanic deposits of the Western Cascades (see map, plate 2).

At the beginning of Cretaceous time, the Klamath Mountains rose as a high island. Slowly this was reduced by erosion, until most of it had been worn below sea level before the close of the Cretaceous. A thin and broken strip of Chico (Upper Cretaceous) sediments now follows the eastern fringe of the Klamath Mountains from Jacksonville southward for 50 miles, to a point about 5 miles southeast of Yreka, on the edge of Shasta Valley. Small outliers also overlie the bedrocks to the west. Apparently the older Cretaceous formations, the Knoxville and Horsetown, which outcrop in the vicinity of Roseburg, are missing in this southern area.

The Chico formation rests on many kinds of schist and plutonic rocks, and its composition shows a corresponding variety. Most of it consists of fine-grained arkosic sandstone interbedded with shale and, especially near the base, with layers of coarse conglomerate. In many places, placer gold has been obtained from the lower part of the formation, as in the Jacksonville district and south of Hornbrook. Where the Chico was derived by erosion of metavolcanics and basic plutonics, it is characteristically a greenish graywacke; where it was derived from acid plutonics, it is generally a pale arkose rich in milky quartz. Elsewhere, it is markedly micaceous, indicating provenance among the metasedimentary formations of the "bedrock series." The maximum thickness of the Chico in the Ashland-Medford valley is approximately 600 feet.

All the Chico beds were laid down in shallow water. The predominance of sandstone, the prevalence of conglomeratic layers, the occurrence of much carbonaceous material in certain horizons and of abundant and large shallow-water fossils, and the manner in which the sediments vary with the nature of the neighboring bedrocks suggest near-shore deposition.

No Chico rocks are known between Yreka and the head of the Sacramento Valley, but there they reappear. On the west side of the valley, in the Coast Ranges, their thickness may be several thousand feet, but on the east side, on the flanks of the Sierra Nevada, they thin rapidly in the direction of Lassen Peak. Whether or not they pass beneath the Cascade Range in the Lassen region is a debatable question,


ALLUVIUM.
PUMICE AND SCORIA FLOWS OF MT MAZAMA.
DACITES OF MT. MAZAMA.
ANDESITES OF MTS. MAZAMA AND SHASTA.
BASALTIC CINDER CONES.
OLIVINE BASALTS OF SHASTA VALLEY AND UPPER SPRAGUE VALLEY. PROBABLY PLEISTOCENE.
PRE-MAZAMA VOLCANOS OF THE HIGH CASCADES. OLIVINE-BEARING BASALTS & BASIC ANDESITES
INTRA-CANYON OLIVINE BASALTS OF THE HIGH CASCADES. PLIOCENE.
PLIOCENE BASALTS EAST OF THE HIGH CASCADES BROKEN INTO FAULT BLOCKS
PLIOCENE DIATOMITES.
EOCENE TO MIOCENE VOLCANIC ROCKS OF THE WESTERN CASCADES AND SPRAGUE RIVER VALLEY
INTRUSIVE ANDESITES OF SHASTA VALLEY
INTRUSIVE RHYOLITES OF SHASTA VALLEY
SILLS AND DIKES IN THE UMPQUA FORMATION
EOCENE DIABASES OF THE ROSEBURG REGION.
EOCENE UMPQUA FORMATION
CRETACEOUS CHICO FORMATION.
JURA CRETACEOUS MYRTLE FORMATION KNOXVILLE ETC
MISCELLANEOUS 'BEDROCKS'. GRANODIORITES, GABBROS AND SERPENTINES WITH META-VOLCANICS & META-SEDIMENTS.
0 6 12 MILES 18 24 30
N
Rogue R.
Medford
Jacksonville
Ashland
KLAMATH-SISKIYOU MOUNTAINS
KLAMATH MOUNTAINS
Siskiyou
Klamath R.
Crater Lake
Klamath Marsh
Chiloquin
Sprague R.
Upper Klamath Lake
Klamath Falls
Lower Klamath Lake
Lost R.
Swan Lake Valley
Poe Valley
Saddle Mt.
Lake of the Woods
Pelican Bu.
Mt. McLoughlin
Klamath-Ashland Hwy.
Parker Mt.
Copco Lake
Butte Valley
Eagle Rock
Willow Creek Mt.
Ball Mt.
Goose Nest
Little Deer Mt.
Deer Mt.
Black Crater
Shasta Valley
Yreka
Mt. Shasta
Black Bu.
OREGON
CALIFORNIA
122°0'

# RECONNAISSANCE GEOLOGIC MAP OF THE CASCADE RANGE
## NORTHERN CALIFORNIA - SOUTHERN OREGON.

Based on surveys between 1931-39 and the following U S G S maps Roseburg & Riddle Sheets after Diller, Medford Sheet partly after F G. Wells, Klamath Sheet partly after B N Moore

H W del.

Reconnaissance Geologic Map of the Cascade Range, Northern California and Southern Oregon

though the occurrence of saline springs south of Lassen Peak suggests that the volcanic rocks may be underlain locally by marine deposits. Diller was of the opinion that an arm of the Chico sea, the "Lassen Strait," ran between the Klamath Island and the Sierra Nevada and spread eastward as far as the Blue Mountains of northeastern Oregon. Patches of Cretaceous rocks in the Prineville and John Day regions lend some support to this view.

We may therefore suggest, though admitting lack of proof, that in Upper Cretaceous times the site of Crater Lake was part of a wide and shallow sea bordered by the Sierra Nevada and Blue Mountains and containing many low islands of bedrock, the largest of which lay where the Klamath and Siskiyou mountains now rise.

### Eocene Formations

At the close of the Cretaceous period, the distribution of land and sea was greatly changed. The sea retreated westward beyond the line of the Cascade Range, never to return, and its place was taken by a gently undulating plain. Weaver[1] suggests that uplift of the Cretaceous rocks in southwestern Oregon forced the sea even farther west than the present coast line, though to the north the recession was considerably less. During Middle Eocene time, slight downwarping of the plain permitted the sea to readvance over northwestern Oregon to a shore line that ran approximately from the vicinity of Roseburg through Portland to Seattle. Farther south, in the Klamath-Siskiyou region and in the Ashland-Medford valley, the Lower and Middle Eocene was a time of nondeposition, and it is likely that the mountains were rising isostatically in response to erosion.

Volcanic activity had already commenced in eastern Washington during the early Eocene, as is shown by the lavas and pyroclastic deposits of the Naches formation. Between Lower and Middle Eocene times volcanism increased in intensity and became more widespread. From Roseburg north to Vancouver Island, tremendous eruptions occurred. Most of the lavas were basic and many escaped from submarine fissures in the form of pillow basalts, as in the Roseburg region, 40 miles west of Crater Lake. Accompanying the flows were explosions of fragmental debris, so that the sediments accumulating in the Eocene seas were highly charged with tuff.

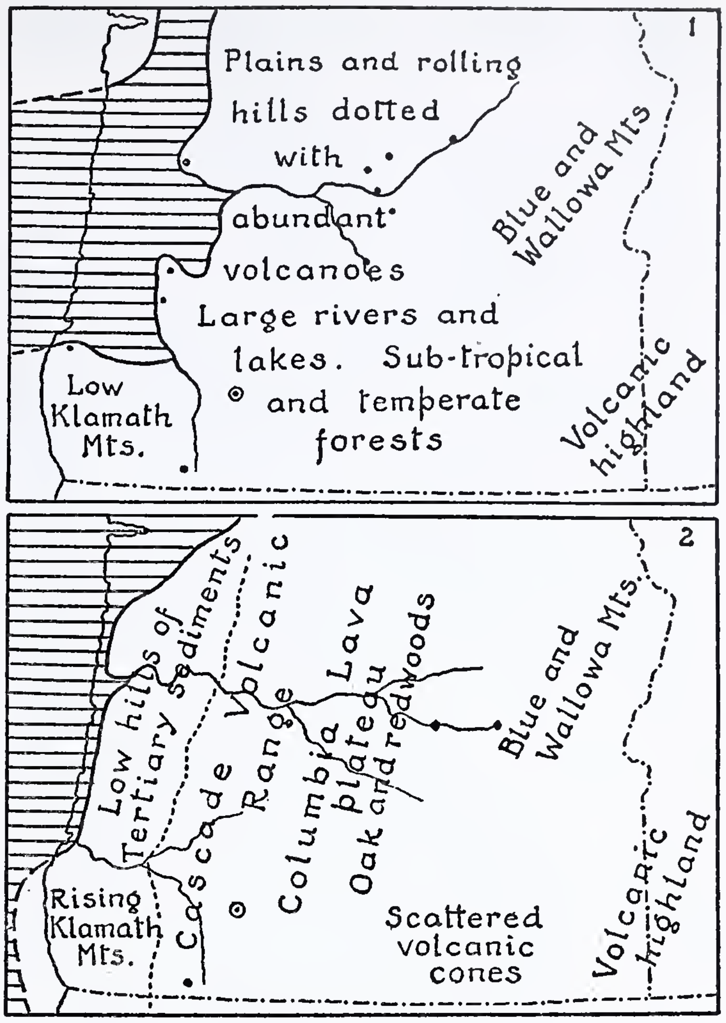


Fig. 1. Paleogeographic maps of Oregon: 1, late Eocene times; 2, late Miocene times. Shaded areas indicate seas. Dots indicate localities where fossil floras have been found. Position of Crater Lake shown by dot within circle. (Based on maps by Chaney and Weaver.)

A shallow marine embayment continued to occupy most of northwestern Oregon in Upper Eocene times, its southern limit following a line westward from Roseburg to the present coast. Farther south, between Roseburg and the head of Evans Valley (see map, plate 2), Eocene sediments seem to be absent. This appears to have been a region of continuous erosion throughout the Eocene period. But still farther south, from Evans Valley, through the Ashland-Medford valley, as far as Shasta Valley in California, 60 miles distant, there is an unbroken belt of Upper Eocene sediments, referred to as the Umpqua formation.

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[1] C. E. Weaver, "Tertiary stratigraphy of western Washington and northwestern Oregon," Univ. Washington Publ. Geol., vol. 4, 1937.

However, unlike the Umpqua formation of the Roseburg area, which is entirely marine, the Umpqua here is largely, if not wholly, of fresh-water origin.

The fresh-water Umpqua formation rests disconformably and perhaps in part with slight angular unconformity on the Chico formation in this southern belt. According to Wells,[2] it attains a maximum thickness of about 8000 feet in the Medford quadrangle. In Evans Valley, it rests directly on the bedrocks and consists mainly of arkosic sands with pebbly layers, shales, and several thin seams of coal. Around Beagle, in Sams Valley, and under the lava cappings of Table Rock, the Umpqua marls and sands, largely derived from acid plutonic bedrocks, carry abundant fragments of silicified wood. In the Ashland-Medford valley, where the formation reaches its fullest development, the sediments are chiefly sandstones, shales, and conglomerates, the latter heavily charged with pebbles and boulders of quartzite, milky quartz, and chert. In the upper part of the formation, volcanic material becomes increasingly abundant. It is therefore impossible to draw any sharp boundary between the Umpqua and the overlying Western Cascade volcanic series. Close to the Rogue River, the transitional water-laid volcanic detritus reaches a thickness of 2000 feet.

Noteworthy in the fresh-water Umpqua beds of the Ashland-Medford valley are the coal seams which outcrop in their upper part. According to Diller, they improve in quality as they are followed northeastward in the direction of dip. The rich flora recovered from these coals implies the existence of swamps along the border of the rising Klamath Mountains.

In California, no exact line has yet been drawn between the Chico and Umpqua formations, but the latter consists chiefly of blue-black shales and sandstones, with occasional seams of coal, as at Agar on the edge of Shasta Valley. Here also the Umpqua becomes increasingly rich in tuffaceous material in its upper part.

In brief, a thick series of river-borne sediments accumulated during Upper Eocene times along the northeast and east slopes of the Klamath Mountains. Here and there, on a low, rolling surface, were swamps bordered by dense subtropical vegetation. Volcanic activity, which had started earlier farther north, extended to this region toward the close of the Eocene, and thick deposits of ash and agglomerate were laid down between layers of fluviatile material. Finally, before the onset of the main volcanic eruptions that built the Western Cascades, there was a gentle uplift of the Umpqua beds near the Oregon-California boundary, for whereas the Western Cascade series rests conformably on the Umpqua in the northern half of the Medford quadrangle, a marked angular discordance divides them to the south. Still farther south, along the edge of Shasta Valley, the Western Cascade lavas gradually overlap the Umpqua beds and the underlying Chico and finally come to rest on the bedrocks.

There is little doubt that the marine Umpqua beds of the Roseburg region and the fresh-water Umpqua beds of the Ashland-Medford valley pass eastward under Crater Lake and interfinger with the continental Eocene sediments and tuffs east of the Cascade Range. While the Umpqua formation was being deposited west of the Cascades, a broad plain existed to the east. At that time there was no high divide as now. On the eastern plains, volcanoes were erupting the lavas and tuffs of the Clarno formation in the John Day Basin, and streams were depositing torrential gravels. The conditions that must then have obtained have been well described by Chaney:[3]

> In Eocene time the vegetation across the state (Oregon) was essentially uniform. The avocado (*Persea*), cinnamon (*Cinnamomum*), fig (*Ficus*), and persimmon (*Diospyros*) found in the Goshen flora near Eugene or in the Comstock flora to the south are identical with those which lived in the John Day Basin. Of more than forty species of trees, shrubs, and vines which make up the Clarno flora, there are only four or five which have not been found in older Tertiary rocks along the Pacific slope from Washington to California. The conclusion is inescapable that the mild and humid climate of the coastal borders extended inland to the John Day Basin of eastern Oregon, over the area now occupied by the Cascade Range. For if a mountain barrier had divided Oregon during the Eocene, the fossil floras would have been as different as they are across the state today. . . . Growing on the lower slopes of the Andes in Venezuela, on the

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[2] F. G. Wells, "Preliminary geologic map of the Medford quadrangle," Oregon State Dept. of Geology and Mineral Industries, 1939.

[3] R. W. Chaney, "Ancient forests of Oregon: a study of earth history in western America," Cooperation in Research, Carnegie Inst. Wash. Pub. 501, pp. 631–648, 1938.

savannas of Panama, and in the mountains of Costa Rica and Guatemala there are trees with leaves, fruits, and stems like those of the Clarno and other Eocene floras.

In the hills overlooking the plains, the subtropical vegetation was mixed with trees of temperate species, such as the redwood, alder, tan oak, and elm. Between the hills ran broad rivers that were dammed from time to time by flows of lava and outpourings of ash. Where the volcanoes were situated, it is impossible to tell, but that they were more widely scattered than the later volcanoes of the Cascade Range cannot be doubted from the distribution of their products. The low coast line swung west and north by Roseburg, and to the south the Klamath Mountains were slowly rising.

## The Western Cascade Volcanic Series

The Pliocene and younger volcanic cones on the crest of the Cascade Range are flanked on the west by a belt of older Tertiary lavas and pyroclastic rocks named by Callaghan[4] the Western Cascade series (see map, plate 2). Throughout this belt, the topography is mature and dendritic tributaries make their way between high, narrow-crested ridges to feed the major, westward-flowing rivers, the Klamath, Rogue, Umpqua, and Mackenzie. There is no trace here of the constructional slopes that characterize the High Cascades, for the rocks of the Western Cascades had already been folded and deeply eroded before the volcanoes of the High Cascades began to erupt.

### *Age of the Western Cascade Series*

Much work remains to be done before the precise age of these rocks can be determined, though enough is already known to suggest that, in general, volcanic activity commenced later at the southern end of the belt than farther north.

In Washington, as we have seen (p. 11), volcanism began as early as Lower Eocene time. In the Roseburg area, volcanoes had certainly commenced to erupt by Upper Eocene time, at first beneath the sea and later on land, for the lower part of the Calapooya formation, a local member of the Western Cascade series, contains an Upper Eocene subtropical flora similar to that of the Clarno formation of the John Day Basin. Farther south, in the Ashland-Medford valley, some of the earliest of the Western Cascade volcanics contain a temperate flora which Chaney[5] assigns to the Lower Miocene or Upper Oligocene. Still farther south, near Hornbrook, in California, the basal tuffs have yielded a flora of Upper Eocene or Oligocene age.[6]

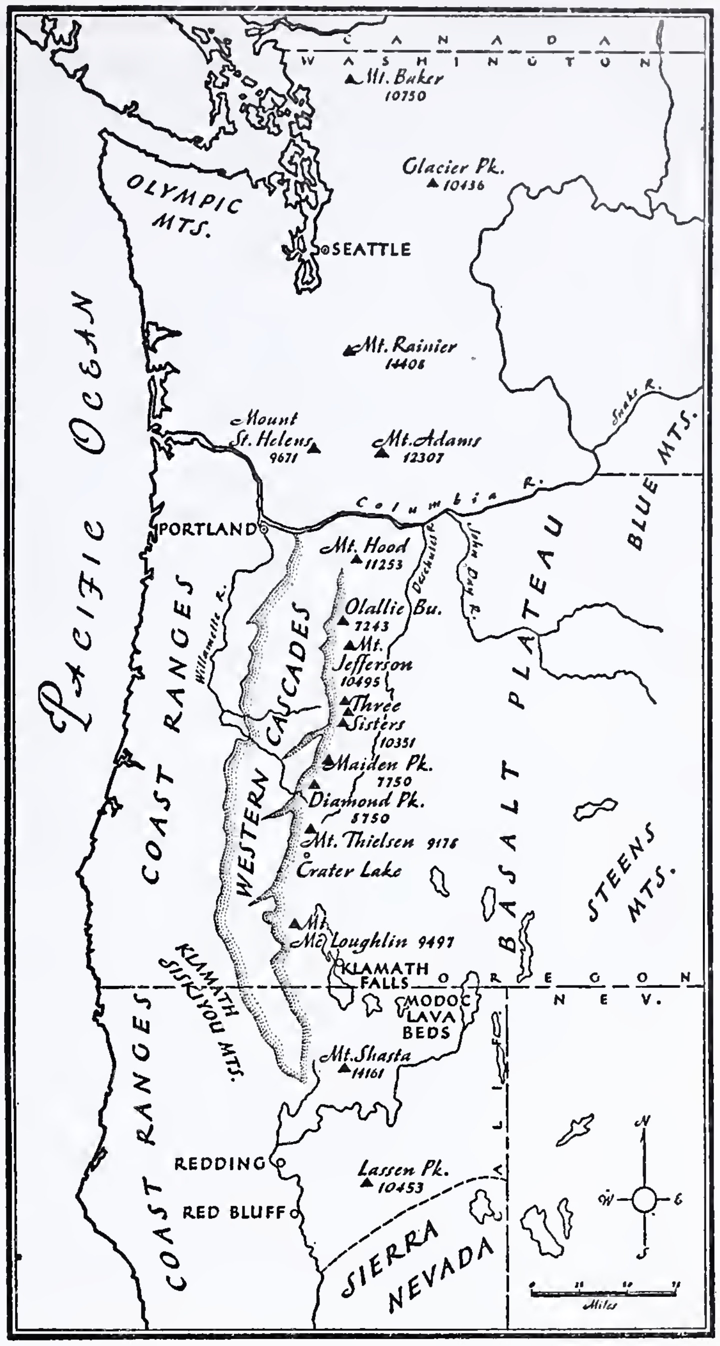

Fig. 2. Map of the Cascade Range. (Drawn by A. W. Severy.)

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[4] Eugene Callaghan, "Some features of the volcanic sequence in the Cascade Range in Oregon," Trans. Amer. Geophys. Union, pp. 243–249, 1933; "Metalliferous mineral deposits of the Cascade Range in Oregon," U. S. Geol. Surv. Bull. 893, 1938.

[5] R. W. Chaney, *op. cit.*

[6] R. W. Chaney, personal communication.

The upper age limit of the Western Cascade series is no less indefinite. Writing of the belt west of Mount Jefferson, in northern Oregon, Thayer[7] states that the basal rhyolites are possibly equivalent to the upper part of the Clarno (Eocene) series east of the Cascades. On these rest water-worked and land-laid pyroclastic deposits, the Breitenbush beds, which he regards as equivalent to the John Day series (Lower Miocene and Upper Oligocene), and then a thick series of lavas, the Stayton and Sardine flows, which probably interfinger with the Middle Miocene Columbia River basalts of eastern Oregon. All these Western Cascade volcanic rocks were folded, faulted, mineralized, and intruded by stocks of diorite, and had been considerably eroded before the High Cascade volcanoes commenced their growth in Pliocene times.

Southwest of Crater Lake, on the slopes of Grizzly Peak, near Ashland, well up in the Western Cascade series though still several thousand feet from the top, Chaney obtained a temperate to warm-temperate Upper to Middle Miocene flora similar to that of the Mascall formation east of the Cascades.

Tentatively, therefore, we conclude that in the part of the Western Cascades closest to Crater Lake, volcanic activity commenced in the Upper Eocene and continued until the close of the Miocene, by which time volcanic rocks had accumulated to a thickness of 7000 to 10,000 feet. And here, as in northern Oregon, this vast series of lavas and pyroclastics had been invaded by stocks of diorite and had been gently deformed before the High Cascade cones began to rise.

Throughout the period when the Western Cascade volcanic rocks were being erupted, there was almost continuous volcanic activity in the region east of the Cascade Range, where the Clarno, John Day, Columbia River, and Mascall formations were being laid down. In the eastern part of the Klamath quadrangle, bordering Sprague River, are several inliers of older volcanics. Moore[8] regards these as equivalents of the Payette (Miocene) formations to the east. There can be no doubt, therefore, that the eastward-dipping volcanics of the Western Cascades pass beneath the Crater Lake region and interfinger with the early Tertiary volcanics on the plateau farther east.

### *Rocks of the Western Cascade Series*

The volcanic rocks of the Western Cascades are made up principally of basic andesites, though they range from olivine basalts to rhyolites. They differ from the rocks of the High Cascades in the much higher proportion of pyroclastic debris, the presence of more interbedded sediment, and the much higher degree of alteration. This alteration is most pronounced in the neighborhood of intrusive bodies, but even far from intrusive contacts the lavas and tuffs are commonly chloritized. In many places, the flows carry carbonates, zeolites, quartz, pyrite, sericite, and epidote, produced presumably by fluids escaping from buried intrusions. In certain lavas, particularly near the base of the series, opal and chalcedony amygdules are abundant; in the interbedded tuffs, silicified wood and fossil leaves are widespread. These features make it easy to distinguish the volcanics of the Western from those of the High Cascades.

Much has already been written elsewhere concerning the volcanics of the Western Cascades, notably by Callaghan,[9] Thayer,[10] and Wells.[11] A brief description must therefore suffice.

At the southern end of the belt, in Shasta Valley, the series consists chiefly of dark, basic andesites and basalts. Some of the flows of andesite carry abundant hornblende, but by far the majority are characterized by augite and hypersthene, and many are heavily charged with amygdules of opal and agate. On the west side of the valley the rocks have been strangely eroded into a multitude of hillocks and ridges that seem from a distance like the products of a recent eruption. On the opposite side, higher in the series, the lavas are increasingly mixed with pyroclastic debris, some in the form of white rhyolite tuff, and some, as on Sheep Rock, in the form of coarse andesitic tuff breccia. Around Copco Lake and in the deep gorge of the Klamath River, andesitic lavas and interbedded rhyolite tuffs are clearly displayed, dipping gently eastward under the basalts of the High Cascades.

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[7] T. P. Thayer, "Petrology of later Tertiary and Quaternary rocks of the north-central Cascade Mountains in Oregon," Bull. Geol. Soc. Amer., vol. 48, pp. 1611–1652, 1937.

[8] B. N. Moore, "Nonmetallic mineral resources of eastern Oregon," U. S. Geol. Surv. Bull. 875, p. 36, 1937.

[9] Eugene Callaghan, *op. cit.*

[10] T. P. Thayer, *op. cit.*

[11] F. G. Wells, *op. cit.*

Farther north, in the Medford quadrangle, where the thickness of the series rapidly increases, the proportion of andesitic and rhyolitic tuff also increases. Layers of volcanic conglomerate and sand indicate that streams were vigorous during the accumulation of the lavas; lenses of shale, some crowded with leaves and others with diatoms, suggest that ponds were dammed by flows and piles of ash. Most of the lavas are black, somewhat glassy pyroxene andesites. With these are occasional flows of hornblende andesite and many of black olivine basalt, but flows of acid lava are quite exceptional. Layers of andesitic breccia and rhyolite tuff recur at many horizons, carrying plentiful leaves and fragments of silicified wood.

Still farther north, the proportion of gray andesitic lavas increases, though dark, glassy pyroxene andesites and olivine basalts continue to be the dominant flows along both the South and North Umpqua rivers. Hereabouts there are cliff-forming layers of rhyolite tuff up to 400 feet in thickness, and many bands of andesite tuff breccia with scattered logs of carbonized wood, probably products of volcanic mudflows (lahars).

It would serve no good purpose to describe the Western Cascade series in more detail. Splendid dip sections are revealed along the major canyons and highways; yet even where these are closely spaced, the sequence of lavas, pyroclastics, and sediments differs greatly.

### *Climate and Flora*

During the long interval between Upper Eocene and Upper Miocene times, when the Western Cascade series was accumulating, the climate gradually became cooler. The subtropical vegetation which flourished in the John Day Basin in Eocene time retreated westward and southward, and persisted during the Miocene in only a few favored places, where it was mixed with a temperate flora. The Oregon forests of the Miocene, writes Chaney,[12] were "like those of today in the valleys of Michigan and Ohio, and in the Redwood Belt of California; they were essentially like those which had lived in the uplands during the Eocene." The climate was mild and moist. Yet even the prolonged volcanic activity of Eocene, Oligocene, and Miocene times cannot have built a high and continuous range separating western from eastern Oregon, for redwoods continued to grow east of the present Cascades, showing that cool, moist sea winds still penetrated far inland as late as Upper Miocene times. Living there with the redwoods, according to Chaney, were black and live oaks, box elders, madroños, plane trees, and poplars. West of the present Cascades, some of the subtropical vegetation persisted in sheltered valleys.

It was not until the High Cascade volcanoes began to rise and the Western Cascade region had been elevated by folding that a mountain barrier shut off eastern Oregon from the supply of rain. Not until then did the redwoods disappear from east of the Cascades, nor until then did the floras on opposite sides of the range begin to show the striking differences we find today.

We may thus conclude that the region about Crater Lake, which had been a low subtropical plain dotted with volcanic cones at the close of the Eocene, had become by the close of the Miocene a fairly high volcanic plateau, clothed with temperate forests, through which flowed many large rivers and on which lay innumerable lakes formed by dams of lava. The coast line lay approximately where it is today.

### INTRUSIONS AND VOLCANIC NECKS IN THE WESTERN CASCADES

The vents from which the lavas and pyroclastic rocks of the Western Cascades were erupted are indicated only by the deeply denuded fillings of the conduits, and even of these few have been recognized. The cones and craters that formerly existed were destroyed long ago.

Too little work has been done to enable us to say whether or not the early Tertiary volcanoes were arranged in any definite manner, though it appears that they were concentrated in a more or less north-south belt parallel to the later volcanoes of the High Cascades. In the Bohemia mining district, Buddington and Callaghan[13] found many small plugs of diorite porphyry and dacite porphyry associated with a stock and several large dikes of granodiorite porphyry,

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[12] R. W. Chaney, *op. cit.*

[13] A. F. Buddington and Eugene Callaghan, "Dioritic intrusive rocks and contact metamorphism in the Cascade Range in Oregon," Amer. Jour. Sci., ser. 5, vol. 31, p. 442, 1936.

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around which the volcanic rocks were metamorphosed and mineralized. Other plugs are known from the North Santiam, Quartzville, and Blue River mining districts. In the Calapooya Mountains, Wells and Waters[14] discovered three necks cutting the Western Cascade lavas, one composed of fine-grained gabbro, a second of quartz-augite diorite, and a third of hypersthene basalt. About 20 miles west of Crater Lake, at the Buzzard (Alserena) mine, there is a large intrusion of rhyolite porphyry. Two small oval plugs of dacite porphyry cut the Western Cascade series near Agate Flat, north of Copco Lake. In Shasta Valley, a line of fine-grained rhyolite porphyry intrusions, some 8 miles long, runs in a northeast-southwest direction through Little Shasta (see map, plate 2). Adjoining these rhyolitic intrusions, close to Little Shasta, are two oval masses of hornblende andesite porphyry, each about a mile across; a third mass of similar rock forms Gregory Mountain, on the outskirts of Montague. Finally, near the south end of Shasta Valley there are two small plugs of hypersthene-quartz diorite porphyry.

How many of these intrusions represent deeply eroded volcanic conduits, it is impossible to say, though some of them almost certainly mark the sites of former vents. An accumulation of lavas and pyroclastic rocks as vast as that of the Western Cascades must have been erupted from a great number of sources. The surprising thing is that so few of the feeders have thus far been found. Since only a few Tertiary intrusions are known to cut the bedrocks farther west, the principal source cannot lie in that direction. On the other hand, many vents may be buried beneath the lavas of the High Cascades to the east.

In addition to the necks and plugs already mentioned, there are countless intrusions, chiefly sills, along the western fringe of the Western Cascades. Scores of these may be seen among the sediments of the Umpqua formation all the way from Shasta Valley to the Roseburg district, and many may be found among the overlying volcanics. These intrusions range in composition from dacite porphyry to norites, the commonest types being augite- and hypersthene-diorite porphyry. Their range in age is probably the same as that of the Western Cascade volcanic rocks, namely, Upper Eocene to Upper Miocene. Adequate descriptions of them may be found in the papers by Buddington and Callaghan and by Wells and Waters to which reference has already been made.

### EARTH MOVEMENTS AT THE CLOSE OF THE MIOCENE

Earth movements had already occurred prior to the beginning of the volcanic activity that built the Western Cascades; they may indeed have been responsible for the onset of volcanism. In the Roseburg area, the basal volcanics lie with marked angular unconformity on the marine Eocene (Umpqua) formation. North of Talent, in the Ashland-Medford valley, the basal volcanics rest conformably on the fresh-water Umpqua beds; to the south a strong discordance separates them.

It is likely also that once volcanic activity commenced, earth movements were recurrent. To the east of the Cascades, the evidence is clear, for the John Day beds are separated by unconformities both from the Columbia River lavas above and from the Clarno formation below. Within the Western Cascades themselves the evidence is less conclusive, for it is difficult to be sure whether angular discordances are a sign of diastrophism or merely the result of overlapping among lenticular volcanic deposits from different sources.

Major earth movements certainly affected the entire volcanic region at the close of the Miocene. It was at this time that the Western Cascade series, in the belt extending northward from Shasta Valley to Medford, acquired its easterly and northeasterly dips. The highest dips, approximately 15°, normally occur among the basal, westernmost rocks, and in general the dips flatten gradually toward the east until, near the margin of the High Cascades, the beds lie either horizontally or almost so. Perhaps this westward increase in the amount of deformation reflects a major uplift of the bedrocks in the Klamath Mountains and the region immediately to the north.

North of the Rogue River, the general trend of the Western Cascades changes to approximately north-south in response to a gradual change in the dips from northeast to east. The dominant eastward dip continues as far north as the Santiam River, where the axes of the folds swing to a northeasterly direction and so continue to the Columbia River. In this northern part of Oregon, as Thayer has shown,[15] the pre-Pliocene volcanics are thrown into a series of broad anticlines and synclines. East of the Cascades, between Bend and the Columbia River, the folds and faults have, according to Hodge,[16] a roughly east-west trend and thus cut athwart the Cascade Range.

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[14] F. G. Wells and A. C. Waters, "Basaltic rocks in the Umpqua formation," Bull. Geol. Soc. Amer., vol. 46, pp. 967–970, 1935.

It was probably during or shortly after this period of folding that many of the dioritic intrusions of the Western Cascades were formed. These and the mineralized sulphide areas associated with them follow the trend of the Cascade Range, running in a north-northeast direction north of the Bohemia mining district and north-northwest south of it. The quicksilver belt farther west is roughly parallel.

Accompanying the folding and intrusions at the close of the Miocene, or perhaps a little later, the north-south fracture system of the High Cascades began to develop. West of Mount Jefferson, the High Cascade lavas abut on an eastward-facing fault scarp cut across the Western Cascade rocks. Thayer[17] believes that before the High Cascade lavas were erupted this scarp was at least 2000 feet high, and that the rise of the block to the west gave the Western Cascades their present elevation. In the region west and southwest of Crater Lake, there is physiographic evidence of a discontinuous, approximately north-south series of faults separating the Western from the High Cascades (see sections, figure 3). West of the contact, the older lavas rise to heights of more than 5000 feet; immediately to the east they lie buried beneath High Cascade lavas at elevations of less than 3000 to 4000 feet. This sudden fall in elevation seems best explained on the assumption of concealed faults with large downthrow to the east.

Still farther south, from Butte Falls to Shasta Valley (see map, plate 2) there is no clear evidence of buried faults; certainly none separates the High from the Western Cascade lavas in the gorge of the Klamath River.

As a result of these disturbances at the close of the Miocene, the Cascades became a high and rugged range, shutting off eastern Oregon from the supply of moisture-bearing winds so that the redwood ceased to grow there and a vegetation not unlike that of today took its place. Perhaps as the Western Cascades were being uplifted, rapid downcutting permitted the principal streams to maintain a westward course, even against the dips of the rocks they traversed, for if the Klamath, the Rogue, and the Umpqua are not antecedent streams it is difficult to account for the manner in which they cross the present mountains.

## The High Cascades between Mounts Shasta and Mazama

We have seen that in the Western Cascades only a few scattered intrusions remain to suggest the position of former vents. In the High Cascades, on the contrary, even the oldest volcanoes preserve much of their original form, and the younger cones have scarcely been modified by erosion.

Viewed as a whole, the High Cascades form a plateau surmounted by steep-sided shield volcanoes of olivine basalt and olivine-bearing basic andesites, and by younger composite cones, chiefly composed of hypersthene andesite, that lie along or near the crest. The latter so far dwarf all other volcanoes in height that one is likely to gain the false impression that the High Cascades are predominantly composed of andesite. On Shasta, McLoughlin, Mazama, Hood, Adams, Rainier, and Baker, hypersthene andesite is either the dominant or the only type of lava. But large as these volcanoes are, they form only a small part of the total volume of lava in the High Cascades, and they are chiefly Pleistocene and Recent accumulations on a far more voluminous basement of Pliocene basalts and olivine-bearing basic andesites. The first recognition of this important fact we owe to Thayer.[18]

The earlier volcanoes of the High Cascades were formed almost exclusively by quiet effusions of basic lava. Explosive eruptions did pile small cinder cones on the summits of some of the basaltic shields, but these were merely weak, culminating explosions. In

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[15] T. P. Thayer, "Structure of the North Santiam River section of the Cascade Mountains in Oregon," Jour. Geol., vol. 44, pp. 701–716, 1936.

[16] E. T. Hodge, "Geological map of north-central Oregon," Oregon Univ. Publ., vol. 1, no. 5, p. 7, 1932.

[17] T. P. Thayer, *op. cit.,* 1936.

[18] T. P. Thayer, *op. cit.,* pp. 1642–1645, 1937.

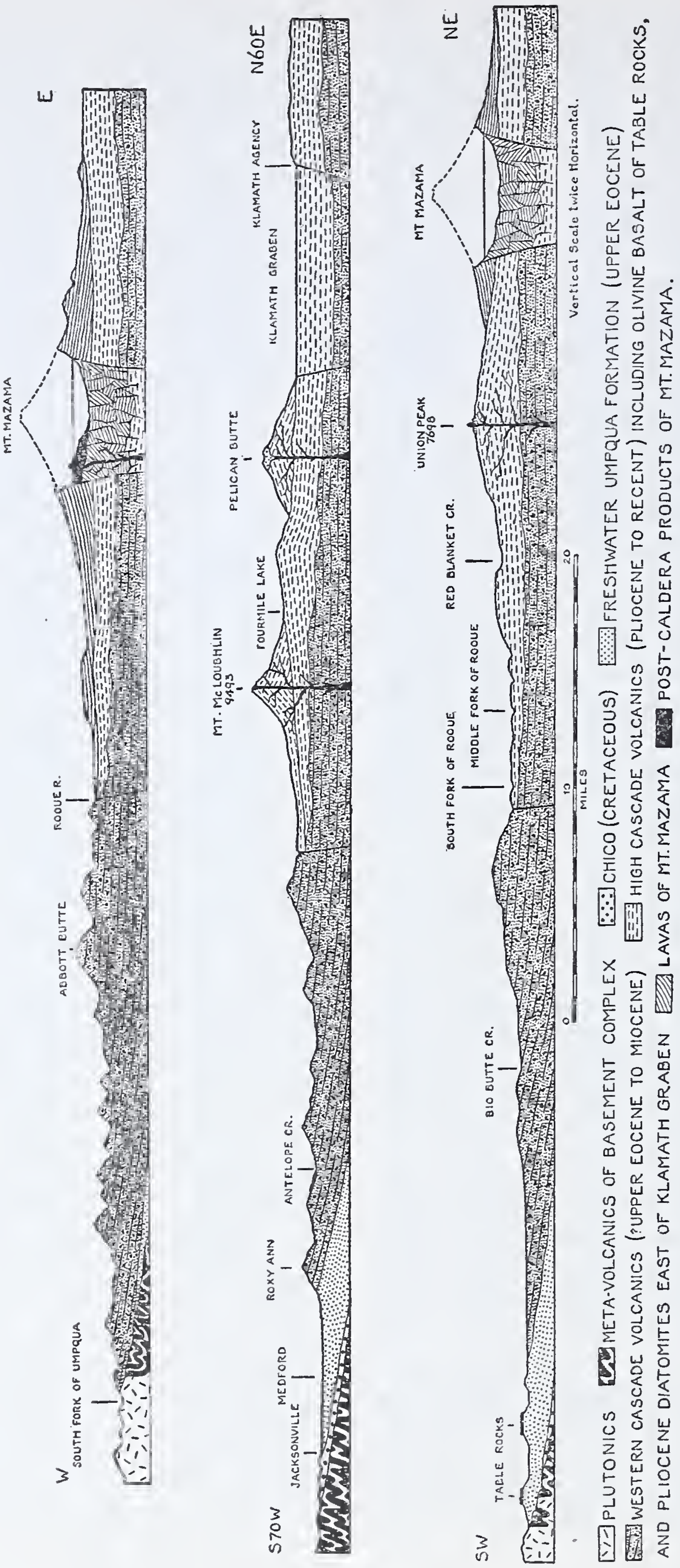

FIG. 3. Sections across the Cascade Range

the younger andesitic volcanoes, on the other hand, explosive activity alternated with quiet effusive activity throughout growth, and in general explosions became more frequent and violent in the later stages. Moreover, in the closing phases the andesitic magma of several of the younger volcanoes was strongly differentiated so that dacites and basalts were erupted, the former as pumice and viscous flows and the latter chiefly as scoria. No such differentiation took place among the older lavas in the southern part of the High Cascades.

For emphasis, then, it may be repeated that the High Cascades in the region that concerns us here were constructed primarily by copious outpourings of basic, olivine-bearing lavas of striking uniformity, some of which escaped from central vents to form steep-sided shield volcanoes of Icelandic type, while others escaped from fissures near the western border of the belt and poured down deep canyons cut through the older lavas of the Western Cascades. While these basaltic volcanoes were active in the High Cascades, others, even more numerous, were erupting wide floods of similar basalt on the plateau to the east.

Toward the close of the Pliocene period, or early in the Pleistocene, at many points along and near the crest of the Cascades a series of imposing andesitic cones began to develop. These include the major volcanoes with which the name Cascades is usually associated. Among them must be counted Mount Mazama, the ancestral cone in the summit of which Crater Lake lies.

The eruption of olivine basalt and olivine-bearing andesite did not cease with the rise of the great hypersthene andesite cones. On the contrary, it went on at the same time from neighboring vents, and has only ceased within the past few centuries. Accordingly, we see in the High Cascades, side by side with the composite andesite cones, well preserved basaltic shield volcanoes, like the Goose Nest, 20 miles north of Mount Shasta, and Brown Mountain.

The salient features of the High Cascades having been enumerated, it seems proper to refer to the results of a reconnaissance of that part of the range which lies adjacent to Crater Lake and extends thence southward to Mount Shasta. For convenience, the description may be separated into two main parts, dealing with (1) the volcanic cones, and (2) the intracanyon flows along the western margin of the High Cascades.

### *The Volcanic Cones*

For the purpose of discussion, the northernmost of the High Cascade volcanoes shown on the map (plate 2) will be described first. Those to the south will then be referred to in turn.

The oldest High Cascade volcanoes to the north of Crater Lake are Watson Butte and Pig Iron Mountain, which coalesce and form an island among flat-topped intracanyon basalts. Obviously these volcanoes had already been deeply denuded before the surrounding basalts were erupted. One of the vents lay near the summit of Watson Butte, where the lavas are associated with tuff breccias and are intruded by many small dikes of dark-green olivine basalt.

Nearer Crater Lake lie the younger cones of Howlock Mountain, Mount Thielsen, and Mount Bailey, the last of which has suffered least from erosion. The flanks of the other two have been excavated into large glacial cirques, and dissection has proceeded far enough to reveal the central conduits. Probably the main activity at all three volcanoes ceased early in the Pleistocene period, while Mount Mazama was still in its infancy, though parasitic flank eruptions built several small cinder cones much later.[19]

Still closer to the northern boundary of the National Park lie the small basaltic cones of Sherwood Buttes and Twin Knobs. These, like the basaltic volcano of Desert Ridge, which falls partly within the park and is therefore described more fully below, have lost their original craters, and their sides have been greatly modified by glacial action.

South of Crater Lake, the High Cascades form a broad plateau built by the confluence of lavas from many basaltic shields. The plateau is incised by glacial cirques and valleys, and most of the shields, though still preserving their general outlines, have been deeply eroded and have lost their summit craters.

Closest to Mount Mazama is the large volcano that culminates in Union Peak, to be described in detail later. The main vent of this volcano may already have become extinct before Mount Mazama commenced to form, but parasitic eruptions occurred on the southeast slope long afterward.

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[19] Howel Williams, "Mount Thielsen, a dissected Cascade volcano," Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 23, pp. 195–214, 1933.

The vent of one of the largest of the basaltic volcanoes lay immediately to the north of Devil's Peak, on the precipitous north side of which may be seen the remains of a tuff-scoria cone, cut by basaltic dikes. This ruined cone once occupied the summit crater of the volcano. Lavas from this source spread across the full width of the High Cascades. Smaller parasitic cones rose not far from Devil's Peak, on Klamath Point and elsewhere.

Another prominent basaltic shield volcano forms Rustler Peak, on the top of which stands a symmetrical dome of pale hornblende andesite. So far as is known, this andesite is the only lava in the entire stretch of the High Cascades between Mounts Shasta and Mazama that relieves the monotony of the olivine basalts and basic pyroxene andesites; and this is the only domical protrusion yet recognized in that stretch of 80 miles.

The next vent toward the south lies near Blue Rock. Here, flows of basalt radiate from a central plug of olivine diabase around which are clustered many dikes of dark-green olivine basalt similar to those seen on Watson Butte. The summit crater of the Blue Rock volcano has been completely obliterated.

East of Blue Rock, and towering above the Klamath graben, is a much younger basaltic volcano, Pelican Butte, crowned by a well preserved cinder cone.

The highest of the volcanoes between Mounts Shasta and Mazama is Mount McLoughlin, formerly known as Mount Pitt, which reaches an elevation of 9493 feet and has a basal diameter of approximately 6 miles. (See plate 5, figure 1.) The lavas of this volcano are somewhat more siliceous and must have been more viscous than the basalts of the neighboring volcanoes, for the slopes of the mountain are much steeper. Toward the summit the lavas become increasingly dark and scoriaceous, as they do on many other Cascade volcanoes, indicating a higher gas content in the later flows. Toward the summit, also, the proportion of interbedded fragmental debris increases. The vent of the McLoughlin volcano lay a little to the north of the present summit, and its position is marked by the ruins of a tuff-scoria cone into which are intruded irregular vertical plugs reminiscent of those cutting the summit tuff cones on Union Peak and Mount Thielsen. In and around the vent there is evidence of much solfataric activity. The most recent flow from Mount McLoughlin, a blocky olivine basalt, escaped from a fissure at the northwest base probably not more than a few centuries ago.

Adjacent to Mount McLoughlin is one of the youngest and best preserved of all the basaltic volcanoes of the High Cascades, Brown Mountain, a perfect shield, some 2000 feet high, topped by a youthful cinder cone. The sides of this volcano are a veritable wilderness of blocky olivine basalt flows so fresh in appearance, so steep-fronted, and for the most part so thinly covered with vegetation that they can hardly be more than a few hundred years old. Robinson Butte, to the west of Brown Mountain, is an older basaltic shield, and its summit cinder cone has almost entirely disappeared.

Between these volcanoes and the Oregon-California line stretches a basaltic plateau dotted with wooded shield volcanoes of Icelandic type. These merit no particular attention; their parasitic and summit cinder cones are shown on the map (plate 2). They consist of extremely uniform pale-gray olivine basalt.

Detached from the main belt are the twin volcanoes of Chinquapin and Little Chinquapin mountains, also made up of homogeneous flows of olivine basalt. At the south base of Little Chinquapin, the underlying lavas of the Western Cascade series are cut by a swarm of dikes trending north 60–65° east, perpendicular to the strike. The position of these two isolated volcanoes seems to be related to a local flexure in the underlying rocks.

Owing to the cover of vegetation, there is little to be seen on the slopes of the shield volcanoes between the Ashland–Klamath Falls highway and the gorge of the Klamath River, but in the walls of the gorge sheets of basalt, averaging 20 to 25 feet thick, are exposed to a depth of more than 1000 feet, lying almost horizontally on eastward-dipping andesites and rhyolites of the Western Cascade series. Apparently a broad and shallow valley already existed along the course of the Klamath River when the neighboring shield volcanoes erupted this succession of flows.

A most interesting field of recent volcanism and one that will repay closer study lies immediately below Copco Lake on the Klamath River. Here, probably within the past thousand years, three basaltic cinder cones were formed along a north-south fissure and from them flows of scoriaceous olivine basalt were erupted. These dammed the Klamath River to form a deep lake, in which much diatomaceous earth accumulated. Accompanying the basic flows, there were protrusions of hornblende dacite in the form of domes and intrusions of columnar basalt.

A north-south cluster of basaltic and basic andesite volcanoes makes up the High Cascades between the Klamath River and Mount Shasta. The older ones, including Herd Peak, Willow Creek Mountain, Eagle Rock, and Ball Mountain, though retaining their topographic individuality, are devoid of summit craters and may date back to the Pliocene period, whereas the younger ones, including Black Crater and the Goose Nest, continued their activity until quite recently. On the flanks of several of these volcanoes are youthful cinder cones (see map, plate 2). East of the main belt rise many more basaltic shields that differ only in being greatly modified by faulting. These merge gradually into a basaltic plateau, capped by recent cones, that stretches eastward to the Medicine Lake Highlands.

Finally, at the south end of the belt rises the magnificent Mount Shasta, a composite cone built up, like Mount Mazama, chiefly of hypersthene andesite and, like the latter, containing far more pyroclastic ejecta than any of the volcanoes that lie between. The similarity between the two is accentuated by the fact that both, in the later stages of activity, erupted viscous flows and domes of dacite and cones of basaltic scoria. At Shasta, these culminating eruptions took place mainly from a north-south fissure traversing the summit, parallel to the main axis of the High Cascades.[20]

### *The Intracanyon and Associated Fissure Flows*

Along the margin of the High Cascades are a series of pale-gray olivine basalt flows that poured down the principal canyons cut across the Western Cascades. Thayer[21] has described such flows under the name Santiam basalts, along the North Santiam River, west of Mount Jefferson, and has shown that they poured down canyons cut in pre-Wisconsin time through the older lavas of the High Cascades. In that region, the intracanyon flows reach a thickness of 1600 feet.

Similar flows occupy the upper stretches of the gorges of the McKenzie River, the North Fork of the Middle Fork of the Willamette River, Salt Creek, the North Umpqua, Rogue River, and Butte Creek. The last three of these are shown on the map (plate 2), and all appear on Callaghan's general map of the Oregon Cascades.[22]

All the intracanyon flows are traceable eastward to the bases of basaltic or basaltic andesite volcanoes in the High Cascades. Their sources, however, were not the central vents of those volcanoes. They seem, rather, to have been poured from fissures near the contact between the High and Western Cascades. Probably, as Callaghan suggests, they represent a long span of time, for although "most of them have been deeply trenched by glaciation and by streams," others preserve surface forms suggestive of a recent origin. Possibly some of them date back to the Pliocene, and the youngest were erupted during the later history of Mount Mazama.

Nothing is more distinctive of these intracanyon flows than their uniform lithology. All are hypersthene-free, olivine-rich basalts. Some, it is true, are pale gray and holocrystalline, and others are notably vesicular, black, and rich in glass, but these are minor differences reflecting variations in gas content and rate of chilling. Noteworthy, also, is the great scarcity, and in most places the complete absence, of any interbedded pyroclastic materials. Clearly, thin flows such as these must have been extremely fluid to pour as far as they did down narrow canyons. Those in the gorge of the North Umpqua traveled more than 20 miles and accumulated to a thickness of more than 1000 feet.

Along the Rogue River, the intracanyon basalts can be traced downstream to a point just below McLeod. At Prospect, their total thickness approximates 450 feet. Eastward, they continue up the Rogue River almost to the northwest corner of Crater Lake National Park, and they outcrop in the tributary Castle Creek at the Natural Bridge, a short distance from the west boundary of the park. Obviously, the canyons of the Rogue and Castle Creek were already deeply incised when these flows were erupted, and Mount Mazama had been in existence for a long time.

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[20] Howel Williams, "Mount Shasta, a Cascade volcano," Jour. Geol., vol. 40, pp. 417–429, 1932; "Mount Shasta, California," Ztschr. f. Vulkanol., vol. 15, pp. 225–253, 1934.

[21] T. P. Thayer, *op. cit.*, 1937.

[22] Eugene Callaghan, "Metalliferous mineral deposits of the Cascade Range in Oregon," U. S. Geol. Surv. Bull. 893, pl. 1, 1938.

Near McLeod, the Rogue River debouches from the narrow gorge carved through the intracanyon basalts and continues for about 15 miles in a broader valley cut across the lavas of the Western Cascades until it reaches the belt occupied by the sediments of the Umpqua formation, a short distance north of Medford. Here, the river passes close to two conspicuous mesas called the Table Rocks, where the tilted Umpqua beds are capped by a horizontal sheet of columnar olivine basalt, 150 feet thick. The freshness of the lava and the fact that it lies horizontally leave no doubt that this basalt belongs to the High Cascade and not the Western Cascade series; presumably it represents the products of a fissure eruption coeval with the intracanyon basalts higher up the Rogue River. A similar occurrence has been observed on Table Rock at the base of the Goose Nest volcano in Shasta Valley.

Voluminous flows of olivine basalt also poured down the canyon of Butte Creek from fissures at the western base of the Rustler Peak, Blue Rock, and Mount McLoughlin volcanoes. On lithological grounds it is impossible to say where the intracanyon flows begin and the lavas of the cones end, though the boundary is indicated approximately by a distinct topographic break at an elevation of about 3600 feet.

Finally, an area of olivine basalt, 60 square miles in extent, forms the eastern half of Shasta Valley, separating the older volcanics of the Western Cascades from the cones of the High Cascades. The source of this basalt must be in concealed fissures at the northwest base of Mount Shasta, and when the lava was erupted it must have been distinctly fluid, for it poured for a distance of almost 20 miles down a gentle gradient. Here and there large tubes traverse the lava, one of which, Pluto's Cave, is traceable for more than a mile and has a maximum bore of 70 by 80 feet. The preservation of ropy surfaces and many "Schollendome," and the general absence of weathering suggest that the flow is more likely Recent than Pleistocene in age.

To summarize: After the folding and faulting of the Western Cascade series and the intrusion of dioritic stocks into them at the close of the Miocene, quiet eruptions of olivine basalt and basic, olivine-bearing andesite built a broad north-south belt of shield volcanoes of Icelandic type. This process probably occupied most of Pliocene time. Throughout this long interval the lavas of the High Cascades underwent little or no differentiation. Toward the close of the Pliocene, or early in the Pleistocene period, a few vents in the High Cascade chain began to erupt hypersthene andesite. These continued to be active throughout the Pleistocene and some have ceased to erupt only within the past few thousand years. They now form the crowning peaks of the range, Mounts Shasta, Mazama, Hood, Adams, Rainier, and Baker. At some of these centers, particularly among those at the southern end of the Cascades, differentiation became more and more pronounced as activity proceeded, until eruptions of hypersthene andesite finally gave way to eruptions of dacite and basalt. On the other hand, at the northern end of the chain, on Mounts Rainier and Baker, hypersthene andesite remained the only type of lava even to the end.

While these andesitic cones grew, the eruption of olivine basalt from other centers did not cease. On the contrary, large basaltic shields were formed at the same time, and extensive floods of olivine basalt poured westward down canyons cut through the older lavas of the High Cascades and the underlying volcanics of the Western Cascades.

We are now in a position to appreciate more fully the details of the geology of Crater Lake National Park, the main theme of this report. Our concern in the pages that follow is with the growth and destruction of one of the andesitic volcanoes, Mount Mazama, and with the irregular basement left by the outpourings of older basaltic cones on which it grew.

## The Union Peak Volcano

The southwest corner of the park is occupied by a dissected volcanic cone that culminates in the sharp pinnacle of Union Peak at an elevation of 7698 feet. (See plate 4, figure 1.) Even though the flanks of the volcano have been deeply excavated by glaciers, it is easy to imagine the original form, for the attitude of the lavas is clearly displayed on the radiating ridges that separate the cirques.

The volcano became extinct either before Mount Mazama began to develop or shortly thereafter. Much later, when the central vent had ceased to erupt, and probably when Mazama had almost reached full height, a fissure opened far down the eastern slope of the Union Peak volcano, and several cinder cones, including the Goose Nest, were built along it. The recentness of these cones and their arrangement along a line directed toward the center of Crater Lake suggest that they are related in origin to the cone of Mazama rather than to Union Peak.

One may see Union Peak from any high vantage point on the rim of Crater Lake and, by turning in the opposite direction, may see Mount Thielsen. The observer must be struck at once by the remarkable similarity of their forms. Closer inspection strengthens this impression. Indeed, so similar are the history and internal structure of these two volcanoes, the largest neighbors of Mount Mazama, that a description of one almost exactly fits the other. Briefly, each is a broad, heavily glaciated lava shield surmounted by a pyroclastic cone which occupies the central crater and is intruded by one or more large plugs forming the topmost crags. Judging by the degree to which the volcanoes have been glaciated, they ended their activity at approximately the same time. Possibly both had already reached maturity before the onset of Pleistocene glaciation.

### *Limits of the Volcano*

It is impossible to tell how far the Union Peak lavas spread, for toward the north and east they pass beneath Mount Mazama and in other directions they merge into identical lavas from other sources. Certainly the shield is at least 8 to 9 miles in diameter and more than 3000 feet high.

Immediately to the west of Union Peak, beyond the confines of the park, lies Huckleberry Mountain. Here are more than 60 square miles of westward-dipping lavas similar to those of Union Peak. On the mountain itself there is no indication of a vent, and it may be, therefore, that the Huckleberry lavas escaped from fissures at the base of the Union Peak volcano. But it would require further study to disprove or verify the alternative view that they are part of an older volcano whose eastern part has been downfaulted and buried beneath the products of Union Peak.

Southward, the Union Peak lavas interfinger with similar flows erupted from vents the positions of which are not precisely known. In fact, from Union Peak southward as far as Mount Shasta, approximately 80 miles away, the deeply scarred plateau of the High Cascades contains almost no other lavas than olivine basalts and olivine-bearing basaltic andesites like those of Union Peak.

It would be interesting to know whether or not the lavas of Union Peak extend beneath the waters of Crater Lake, but there is no conclusive evidence bearing on the point. Certainly they do not appear on the caldera walls, though they approach to within 2½ miles at the head of Castle Creek, and if their dip at that place were projected northward they would occur at a level of approximately 5000 feet in the center of the caldera. If Union Peak lavas once extended this far, one might expect to find fragments of them among the explosive ejecta of Mount Mazama, but neither in the pyroclastic materials of the caldera walls nor in the pumice blown out during the final eruptions have any such fragments been recognized.

### *The Main Shield*

Before glaciers modified its form, the volcano must have had a shape approximately like that of an inverted shield or saucer, as do many Icelandic volcanoes. It was not, however, a simple symmetrical mass, for in the later stages of its growth the products of eruption from the summit crater were augmented by thick and extensive flows from fissures and parasitic cones on the lower flanks. For example, the massive flows of Bald Top undoubtedly issued from lateral fissures. Not far from the base of Bald Top, the pale-gray lavas are cut by irregular intrusions of dark, olivine-rich diabase. Similar intrusions elsewhere in the High Cascades are invariably related to volcanic vents.

There must also have been parasitic vents or fissures at the northeast base of the volcano from which large volumes of lava were extruded. One of these lay on or close to Arant Point. At the base of the bluff are dark-gray, dense lavas characterized by closely set, steep joints. Higher up, the lavas are much paler and the joints more widely spaced. On the summit the flow planes, which are gently inclined elsewhere, stand vertically or at high angles. These features suggest that Arant Point is the eroded remnant of a domical protrusion associated with a short and viscous flow from a near-by vent.

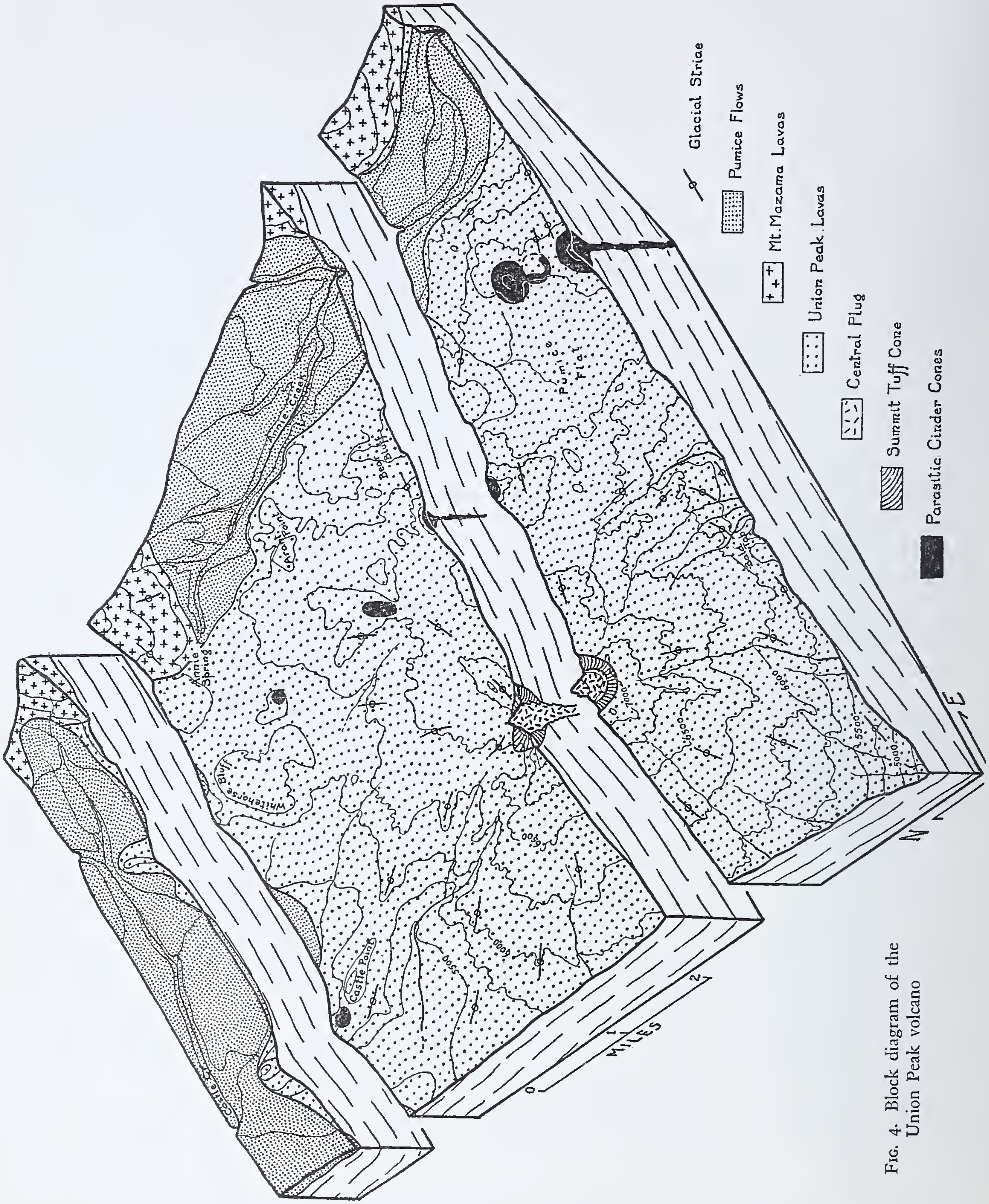
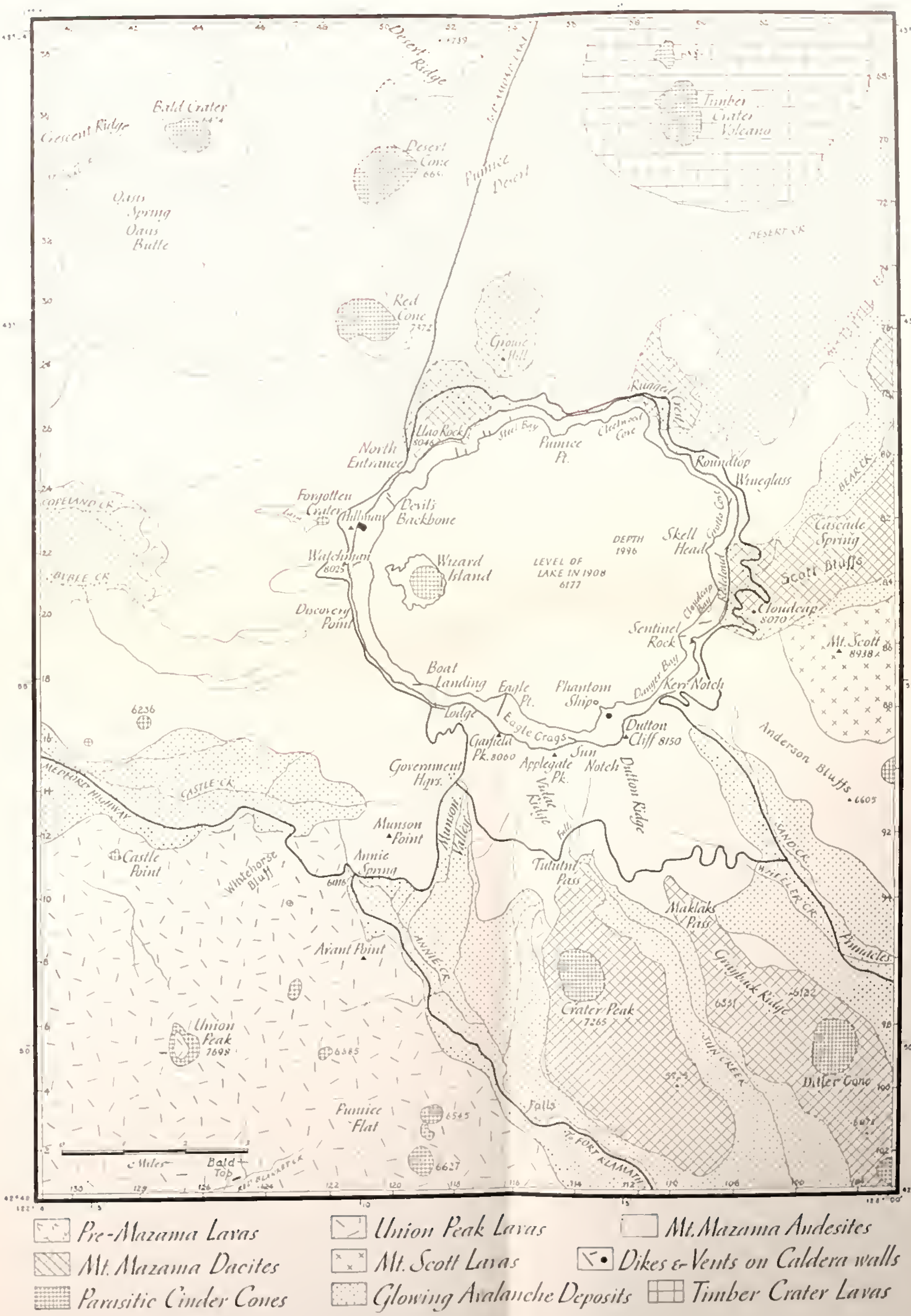


Fig. 4. Block diagram of the Union Peak volcano



Geologic map of Crater Lake National Park

Numbers along margins refer to boundary markers. Elevations in feet. For details of geologic formations on the caldera walls, see panoramic photographs, plates 13 to 29. For contours, see U. S. Geological Survey sheet of the park. (Drawn by A. W. Severy.)

West of Bear Bluff, and at a few other places on Union Peak, there are narrow rock ridges where the flow planes run lengthwise and stand at high angles, as if the ridges represented the fissure feeders of flows. Very likely the thick, flat-topped pile of lava that forms Whitehorse Bluff escaped from such fissures.

But that most of the lavas of the Union Peak volcano were erupted from the central, summit vent is apparent from their quaquaversal dips. It is clear also that most of the flows were quite fluid, for thin sheets may be traced for long distances. Just to the west of the summit pinnacle, as many as twenty-five superposed flows may be seen in a small cliff section, their average thickness being no more than about 3 feet. Elsewhere flows 10 feet thick are not uncommon. Apparently the thicker flows are restricted to the lower slopes of the volcano, and probably most of them escaped from subsidiary vents.

A brief acquaintance suffices to distinguish the lavas of the Union Peak volcano from the andesites of Mount Mazama. The outstanding differences are briefly these: (1) Few of the Union Peak lavas carry large crystals of feldspar such as typify the Mazama flows; (2) they are rarely free from granules of olivine, a mineral notably rare in the Mazama andesites; (3) they are much poorer in basic inclusions; and (4) they are generally much more strongly jointed.

The dominant lava of Union Peak is a pale-gray, extremely dense rock relieved only by specks of olivine and pyroxene and tiny crystals of plagioclase. Normally the lavas weather to pale-gray and whitish crusts, though the joint planes are commonly tinted pink, owing to oxidation of iron by residual gases. In some flows, the tops and bottoms are extremely vesicular. Such scoriaceous flows are invariably darker than the poorly vesiculated flows, and are also distinguished by a higher content of glass. This relation between vesicularity on the one hand, and dark color and abundance of glass on the other, has been observed on many other Cascade volcanoes. Apparently the development of vesicularity leads to quick chilling of the magnetite-rich residual liquor; hence the dark, glassy groundmass. With the lava types just mentioned, and scattered haphazard among them, are deeply reddened flows which must have been exceptionally rich in gas.

Small amounts of cristobalite, tridymite, and opal are ubiquitous in the products of Union Peak. The opal normally occupies amygdules, but the other two minerals usually occur on joint planes or in seams cutting the lavas at random.

Explosive eruptions contributed little to the growth of the Union Peak volcano. The activity was almost wholly of the quiet, effusive type, so that lavas make up at least 95 per cent of the volume. Thin interbeds of red scoria indicate mild Strombolian eruptions at long intervals.

### *Parasitic Cinder Cones*

As a volcano gains in height, there is increasing tendency for eruptions to occur from cracks on the sides. This was the case at Union Peak. Not only were lavas erupted from lateral fissures, but several parasitic cinder cones were formed along them (see map, plate 3). All have been so modified by glacial action that little of their original form remains.

The best-preserved cone lies on the crest of the ridge immediately north of Castle Point, close to the northern base of the volcano. Here, a crescentic mound of cinders marks part of an old crater rim, but the eastern side of the cone has completely disappeared. Few of the fragments exceed a foot in diameter, and most are ovoid or subangular. They consist of red, brown, and black lapilli and bombs, among which may be found a few ropy lumps with iridescent, glassy skins. Possibly some of the thin lava flows with red, slaggy interbeds, exposed to the north of the cone, were earlier products of the same vent.

About 2 miles east of Union Peak, on 6885 Hill, dark, vesicular lavas are capped by scoria and agglutinate; a mile to the northwest is a round-topped, oval hill made up of scoria fragments and blocks of basalt up to 3 feet across; a third patch of scoria crowns the conical butte south of Whitehorse Bluff. These are the remains of other parasitic cones the craters of which have been obliterated by the passage of ice.

The recent cones close to the eastern base of the Union Peak volcano were formed, as we have already noted, long after the volcano became extinct, and since they belong to the activity of Mount Mazama their description is deferred.

### *The Summit Cone*

After the main lava shield had been built, a small pyroclastic cone developed in the summit crater. The bedded ejecta of which this cone is composed abut sharply against the surrounding lavas in such a way as to suggest that the original crater was steep-walled and deep. Except on the north side, the limits of the cone are easy to locate and enclose an approximately oval area, ⅔ by ½ mile across, elongated parallel to the general trend of the Cascade Range.

Most of the cone is made up of well bedded, pale-buff lapilli tuff and tuff breccia, in which fragments up to 18 inches in diameter lie in a calcareous, sand-like matrix of tuff. Nearer the summit pinnacle, the ejecta become increasingly scoriaceous and ultimately give way to beds of black "cinders" and agglutinate. The earlier eruptions of the summit cone must therefore have been of Strombolian type, the magma being erupted in viscous, incandescent clots, some of which when they fell were sufficiently pasty to adhere to neighboring fragments. Gradually, as activity continued, the eruption of bombs and lapilli of viscous magma diminished, and fine ash and solid fragments of old lava were blown out at lower temperature.

Around the periphery of the cone the dips of the ejecta are low, but inward they steepen beyond the normal angle of repose for such materials. A similar inward increase in the dip of the tuffs may be noted on the summit cone of Mount Thielsen. In both cones, the disturbances must be attributed to intrusion of central plugs of lava.

### *The Summit Plug*

The conspicuous pinnacle at the top of Union Peak owes its existence to a vertical-sided intrusion into the summit cone. So does the great monolith of Thielsen. The Union Peak plug, like the enclosing cone, is approximately oval in outline and elongated in a north-south direction. It measures ½ by ⅓ mile across. The material of which it is composed does not differ essentially from the lavas of the surrounding shield, though much of it is slightly coarser. By far the dominant rock is a pale-gray, massive lava cut by strong joints of irregular trend, the spacing of which generally becomes closer toward the margins of the intrusion. Locally this pale lava is microvesicular, but large vesicles are rare. Flow banding is obscure. Along the northern base of the intrusion, the banding may lie flat or dip inward at low angles, but elsewhere it dips inward steeply or stands vertically. Associated with the pale lava is a darker and denser lava which seems to have been injected later.

After the plug had congealed in the central conduit, iron- and silica-bearing gases continued to rise through it, depositing plates of hematite and crystals of tridymite and cristobalite on joint faces and on the sides of irregular vesicles. Especially fine specimens may be obtained near the eastern margin of the plug on the trail to the summit.

Mention may be made in passing that on the topmost crags of Union Peak the lava has suffered considerable fusion from strokes of lightning. Particularly is this the case on the edges and corners of protruding rocks, though flat faces may also be coated with thin ribbons of olive-green, vesicular glass and punctured by tiny glass-lined pits. Diller has described similar fulgurites from the summit of Mount Thielsen.[23] They are rarely absent from the summits of the higher volcanoes of the Cascade Range.

Finally, when the plug was intruded into the summit cone of Union Peak, it not only deflected the bedding of the enclosing tuffs, but enveloped part of the cone and carried it upward. This explains the occurrence of three detached masses of well bedded, gray and black, scoriaceous tuff breccia within the plug.

Whether the lava forming the Union Peak plug rose above the floor of the summit crater as a steep-sided Pelean dome or spine, or failed altogether to escape from the conduit, cannot be determined. The manner in which the included and enclosing tuffs were disturbed suggests that when the lava rose it was extremely viscous. Even after parts of the plug had solidified, there may have been continued differential uplift as new magma came from below. Such uplift might account for the polished and slickensided faces found on some of the blocks near the summit. The blocky carapaces of Pelean domes commonly show the effects of differential movement in this manner.

To summarize, the Union Peak volcano was built by long-continued outpourings of fluid lava, chiefly from a central vent, but in the later stages from fissures on the flanks. These formed a broad, low shield. Explosive eruptions on the sides of the shield then formed several cinder cones, while other explosions from the central vent built a summit cone within the lava-walled crater. Finally, a viscous mass rose in the central conduit and congealed there as a rigid plug.

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[23] J. S. Diller, "Fulgurite from Mount Thielsen," Amer. Jour. Sci., ser. 3, vol. 28, pp. 252–258, 1884.

### Other Pre-Mazama Lavas within the Park

The lavas occupying the northwest corner of the park and the slopes that lead thence to the Rogue River are composed principally of olivine-rich basaltic andesites similar to those of the Union Peak volcano. Some of these lavas are related to Red Cone, Desert Cone, and Bald Crater, but most of them are much older. Although they are not exposed on the walls of Crater Lake, there is little doubt that they form the foundation beneath Mount Mazama and are of approximately the same age as the lavas of Union Peak. In other words, they belong to the older volcanic series of the High Cascades and antedate the great composite cones. Probably they were erupted in Pliocene and early Pleistocene times.

Generally there is little difficulty in distinguishing these lavas from those of Mount Mazama, for they are usually rich in granules of olivine and devoid of the large feldspar crystals that characterize the Mazama flows. Most of them are so fine-grained that only grains of olivine and pyroxene and specks of feldspar can be recognized by the unaided eye. In color they range from pale gray to black, and, as on Union Peak, the darker flows are usually more vesicular. Some types are holocrystalline and have an ophitic texture; others include much glass and are darker.

Diller referred to these lavas as the Desert Cone and Red Cone basalts on the assumption that they were erupted from those vents, but although similar flows do occur on these cones and in their immediate vicinity, most of the lavas in the northwest corner of the park are much older. This is not to deny that some of them may have been erupted from older vents beneath those cones; indeed, the attitudes of the flow planes point to sources thereabouts. Possibly the youthful Red and Desert cones were the result of renewed activity at vents which had lain dormant throughout the growth of Mount Mazama. (See plate 4, figure 2.)

Not all the pre-Mazama lavas of this region issued from vents near the parasitic cones just mentioned; many are related to the ruined volcano of Desert Ridge. The thick glaciers that once swept down the north side of Mount Mazama almost completely buried this volcano, subjecting it to severe erosion. There is now no trace of a summit crater. Nevertheless, the vague flow banding of the lavas suggests a vent on the north boundary of the park, near post 51. Apparently the volcano was built entirely of lava. Precisely similar flows form the younger volcanoes of Twin Knobs and Sherwood Buttes, respectively 4 and 6 miles to the northwest.

Similar lavas also form the pedestal beneath Bald Crater and the spur running northwest therefrom, and presumably Bald Crater, like Red and Desert cones, marks the site of a vent which burst into renewed activity about the close of the Pleistocene.

Finally, reference should be made to the olivine-bearing lavas forming the mesas on either side of National Creek. On Crescent Ridge these lavas are exposed to a thickness of more than 1500 feet, and throughout this great pile there are no interbeds of fragmental debris. The source of the flows must lie to the east, probably in the vicinity of some of the ruined volcanoes already mentioned.

Hence, during the Pliocene and perhaps also during the early Pleistocene, before the cone of Mount Mazama began to form, the northwest corner of the park was occupied by a group of volcanoes the activity of which was marked by quiet effusion of liquid, wide-spreading, basic lavas, and an almost complete absence of pyroclastic explosions. Mount Mazama rose in the depression between this group of volcanoes on the north and the Union Peak volcano on the south.

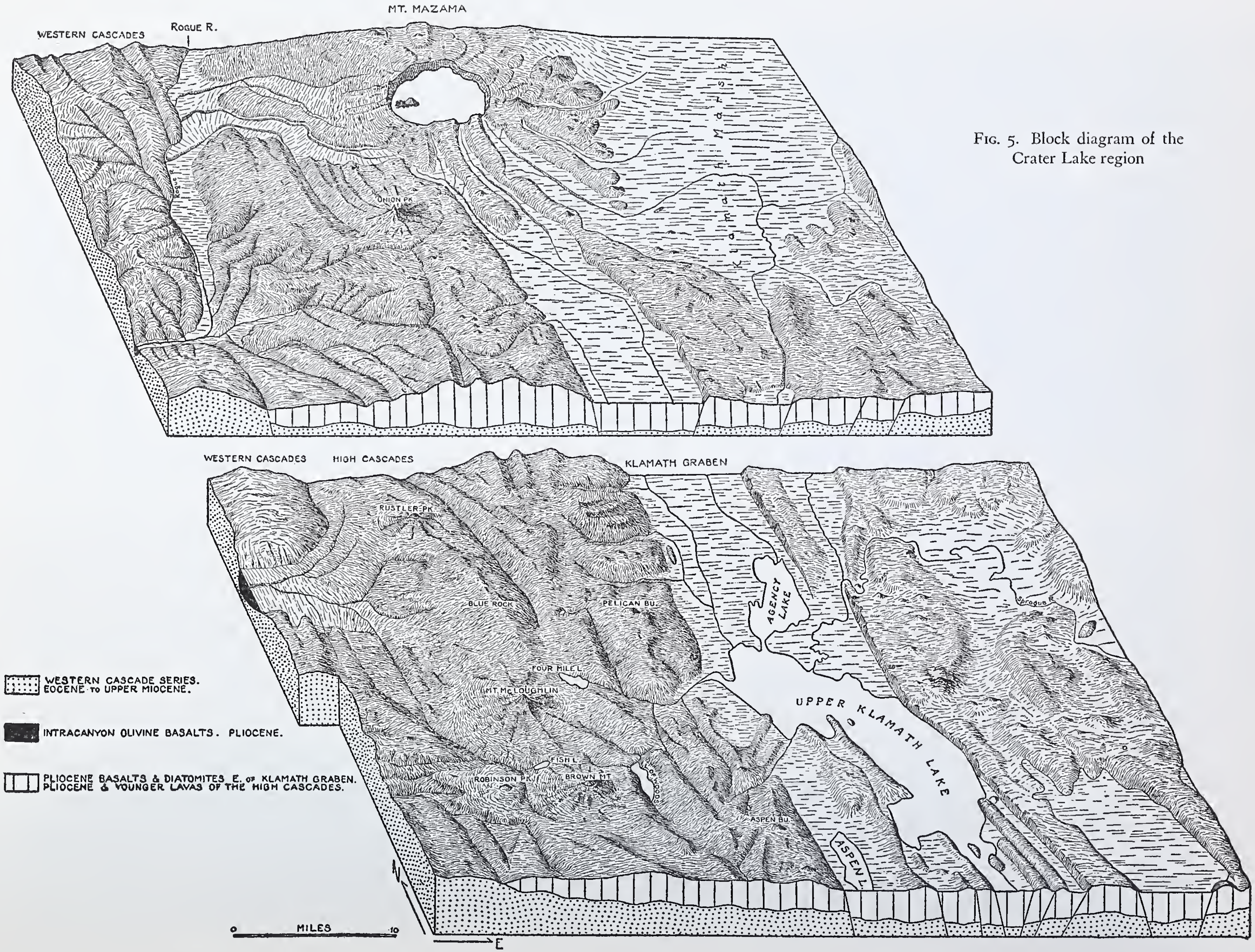

FIG. 5. Block diagram of the Crater Lake region

# The Structural Setting of Mount Mazama

In the part of the Cascade Range shown on the map (plate 2), the pre-Pliocene volcanic rocks dip, in general, toward the east and northeast beneath the lavas of the High Cascades, and their dip diminishes in an easterly direction. Where they finally pass beneath the Pliocene flows, they lie almost if not quite horizontally.

Not only were the volcanic rocks of the Western Cascades folded at the close of the Miocene, but, as we have seen already, they were cut by a system of north-south fractures and invaded by a series of north-south stocks of diorite, around which the older lavas were widely mineralized. It was this north-south fracture system that located the sulphide areas of the Western Cascades and the position of the High Cascade volcanoes.

In the plateau province east and southeast of Crater Lake (see plate 5, figure 2), the trend of the faults is mainly northwest-southeast. This is clearly indicated in the region about Klamath Falls (see block diagram, figure 5).

Immediately south of Crater Lake, the edge of the High Cascades is defined by a north-south fault forming the western boundary of the Klamath graben. Near the California-Oregon line, this fault breaks into a group of minor faults which are offset by the northwest-southeast system of fractures. Indeed, intersection of north-south with northwest-southeast faults seems to be characteristic of the border zone between the High Cascades and the plateau to the east. Moreover, as they approach the High Cascades, several of the northwest-trending faults swing to a north-northwest direction. This is noticeably true of the faults forming the eastern border of the Klamath graben.

Possibly the position of the younger cones of the High Cascades is determined by intersection of the north-south fractures with these oblique faults approaching from the east, and possibly Mount Mazama itself lies at the crossing of the main High Cascade fracture with the largest of the oblique fractures, that forming the eastern boundary of the Klamath trough. Where this oblique fracture disappears beneath the lavas of Mount Mazama at the southeast corner of the National Park, it is directed toward the center of Crater Lake, and if it continues thus far it must there intersect the north-south fault that forms the western wall of the Klamath graben.

The faults of the Klamath region cut Pliocene basalts and diatomites, and, according to Moore,[1] they are "probably no older than uppermost Pliocene." Many of them are marked by scarps which seem too fresh to be older than Recent.

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[1] B. N. Moore, "Nonmetallic mineral resources of eastern Oregon," U. S. Geol. Surv. Bull. 875, p. 40, 1937.

# The Main Andesite Cone of Mount Mazama

## Nature of the Floor and Size of the Cone

A model of Crater Lake and its surroundings is shown in plate 5, figure 3. The irregular floor upon which Mount Mazama was built lay for the most part between 5000 and 6000 feet. When the mountain had reached full height its summit was probably close to 12,000 feet. The completed cone therefore rose 6000 or 7000 feet above the basement. It was in fact a much smaller volcano than many others in the Cascade Range. Mount Shasta, for example, rises 10,000 feet above its floor; its basal diameter is no less than 17 miles and its volume approximates 80 cubic miles. Mount Rainier rises more than 8000 feet above its foundation, and its lavas cover approximately 100 square miles. Moreover, the slopes of the principal cone of Mazama were much gentler than those of Shasta and Rainier.

## Building of the Main Andesite Cone

As far as can be determined, Mount Mazama rose to its greatest height almost solely by eruption of hypersthene andesite. Not until it had practically gained full stature did the feeding magma begin to differentiate toward basalt and dacite.

Of the early history of the volcano there is now no visible record. Presumably, activity began from a single, central vent, though it is clear from the attitudes of the lavas on the caldera walls that early in its growth the volcano was supplied with additional vents, or that the principal vent shifted from time to time.

The oldest of the visible lavas seem to have issued from a vent close to the Phantom Ship, on the south wall of the caldera. We may speak of this as the Phantom vent, and call its products the Phantom cone. The filling of the vent forms a bold triangular face about a third of the way up the caldera wall (plate 6), and is composed of massive, brown-crusted, pale-green vesicular andesite heavily charged with lamprophyric inclusions and cut by darker-green andesite similar to that forming the dikes on Phantom Ship. All but the northern edge of the vent is concealed by talus, but on that side the margin cuts vertically across the enclosing lavas and breccias. In plan, the vent is approximately circular and measures between 200 and 250 yards in diameter.

That we are really dealing here with the filling of an old volcanic conduit is indicated also by the arrangement of the surrounding rocks. Close to the vent lie inward-dipping, red tuff breccias containing blocks of andesite up to 8 feet across. Farther from the vent, toward the lake, the breccias and interbedded lavas dip outward at angles up to 40°. At the base of the spur that projects toward the Phantom Ship, pale-green lapilli tuffs, similar to those on the Ship itself, dip lakeward at high angles. No doubt the Phantom Ship is a remnant of the Phantom cone and the dikes that make its mimic sails are radial offshoots from the central pipe (plate 7, figure 1).

How high the Phantom cone rose it is impossible to tell, for after activity ceased, the summit was eroded and buried by flows and other ejecta from the central vents of Mount Mazama. The unconformity separating the Phantom flows from those of Mazama proper is plainly visible in plate 6. Finally, after the Mazama lavas had entirely buried the Phantom cone, a long period of glacial erosion ensued in this vicinity and a layer of morainic detritus accumulated on the surface. When flows again poured in this direction from the central craters of Mazama, they continued to accumulate to a thickness of more than 1000 feet, and now form the unscalable upper half of Dutton Cliff. The level of this second unconformity is marked by water seeps from the interbedded moraine.

The Phantom cone was, of course, trivial in size as compared with the main cone of Mount Mazama. From the dips of the lavas on the caldera walls, it may be estimated that the principal vents of the major cone lay, not directly above the center of Crater Lake, but between half a mile and a mile to the south, or a little east of south. In other words, Crater Lake is eccentric with respect to the former cone of Mazama. This is suggested at once by the fact that on the south side of the lake the caldera walls are much higher than on the north. The reasons for this eccentricity of the caldera with respect to the cone are discussed later.

## Nature of the Lavas

By far the greater part of Mount Mazama is composed of thin flows of hypersthene-rich augite andesite, similar to the lavas of Mounts Rainier and Baker and the bulk of Mount Shasta. Andesites rich in hornblende with or without biotite are almost completely absent. Invariably the lavas are characterized by abundant and large phenocrysts of feldspar. Texturally, they show wide variation, even within a single flow, from holocrystalline to glassy. Rarely, however, are they as rich in glass as the dacites, nor do they show the hair-fine banding characteristic of the latter. Indeed, except on a broad scale, it is difficult to detect fluxion. In color, the andesites vary from black to pale gray, according to the content of glass, and many flows are pale brown, pink, or dark brick red where they have been affected by escaping gases. Nevertheless, flows which, for these reasons, seem in the field to be of widely different types are singularly alike under the microscope.

One of the most distinctive features of the Mazama andesites is the widespread occurrence of basic inclusions. Few lavas are entirely devoid of them, and in some they make up no less than a quarter of the volume. Generally they are more plentiful among the later flows, where many exceed a foot in length. Most of these inclusions are ovoid and range from 1 inch to 3 or 4 inches across. Compared with the enclosing lavas, they are much more porous and crystalline, and most of them stand out conspicuously in the darker matrix by reason of their pale-gray or pink color. They consist of crisscross prisms of hornblende, pyroxene, and feldspar separated by a small amount of interstitial glass. Similar inclusions are common among the lavas of other Cascade volcanoes; they represent fragments torn from the walls of the conduits and the roofs of the magma chambers as the lavas rose to the surface.

In the great cliff sections along the south, east, and west walls of the caldera, the Mazama andesites usually range between 10 and 80 feet in thickness, most of them measuring between 20 and 30 feet thick. They are considerably thinner than the andesites of Mount Rainier, for which Coombs[1] estimates an average thickness of about 80 feet. But a cursory examination shows that the Mazama flows pinch and swell with great rapidity and that the massive lavas commonly merge into red, slaggy breccias, like those plainly visible on the Castle Crags, east of the Park Headquarters.

As for the jointing of the andesites, columnar structures are rarely well developed. On the other hand, platy or slabby jointing both parallel and perpendicular to the flow planes is seldom absent, and may be so well marked and closely spaced as to give the lavas the appearance of stratified sediments when viewed from a distance. Elsewhere, particularly in Grotto Cove, the andesites are traversed by close-set curved joints at high angles to the banding. The origin of these aberrant structures is not understood.

True scoriaceous (aa), ropy (pahoehoe), or block lavas have not been observed on the walls of Crater Lake. It seems unlikely that original surfaces were destroyed by weathering and erosion prior to burial by later flows and ashes; much more probably the crusts of the flows have always been as smooth as they are today.

In a general way, the lavas of Mount Mazama became thicker as activity progressed. Among the earlier lavas on the caldera walls, few reach 100 feet in thickness. The thickest sheets are practically confined to the upper part of the walls, as, for example, near Discovery Point and along the northern wall. These were erupted at the close of the andesitic period, not long before the main dacitic eruptions began.

The thickest andesites are those of the Palisades and Roundtop. These rest on a thick deposit of glacial debris and were erupted after a long period of quiescence. Presumably they did not issue from the central, summit vents of Mount Mazama, but from fissures far down the northern slope. If this be true, then the eruption of these flows added nothing to the height of Mount Mazama; they were "parasitic" or subterminal flows. We may go even farther and suggest that only the thinner andesites escaped from the central vents of the volcano. It was these that built Mount Mazama to its greatest height. Accordingly, we may speak of the slopes left by the youngest of the thin andesite flows as the *primary slopes* of Mount Mazama, and in trying to estimate how high the volcano formerly rose these are the only slopes to be considered, since the thick flows from fissures below the summit only served to widen, not to heighten the cone.

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[1] H. A. Coombs, "The geology of Mount Rainier National Park," Univ. Washington Publ. Geol., vol. 3, no. 2, p. 173, 1936.

In places, the Roundtop flow is no less than 500 feet thick. Its summit is strikingly polished and scratched by glacial action. The base of the flow has the form of a broad W (plate 25), and rests on coarse, bouldery till. Apparently the lava moved down a U-shaped valley occupied by a medial moraine. The bulk of the flow consists of porphyritic andesite marked by pronounced slabby jointing parallel to the banding. Near the base, the lava becomes darker and increasingly glassy and finally passes into black obsidian. Much of this basal glassy layer is intensely brecciated, and locally it has been reddened by gas action. In crossing the moraines, the lava enveloped many glacial boulders, some as much as 5 feet in diameter.

Immediately to the west of the Roundtop flow is another thick sheet of andesite, forming Palisade Point. This also rests on glacial moraines (see panorama, plate 25). But the top, unlike the top of the Roundtop flow, is extremely irregular, bristling with monolithic crags and traversed by deep, steep-sided fissures, like those which characterize the tops of the later dacite flows. In the upper part of the Palisade flow, the jointing is closely spaced and curved, though generally almost vertical; lower down, the vertical joints are farther apart and produce the crude columnar structure which gives the flow its name. At the base, the lava becomes black, glassy, and autobrecciated. In this flow, ovoid inclusions up to a foot in length make up approximately 5 per cent of the bulk.

Other young, thick andesite flows form the topmost cliffs of the caldera wall overlooking Grotto Cove. These likewise rest on glacial deposits and dip outward at much lower angles than the thin andesites forming the "primary slopes" of Mount Mazama (panorama, plate 24). Probably they were erupted from fissures far below the summit of the volcano. The thick flow immediately south of the Wineglass certainly issued from a feeder at the Wineglass itself, for where the cup joins the stem of the glass, the arrangement of the columns shows that the lava rose through a steeply inclined conduit before spreading at the surface (plate 25). Still other thick andesitic lavas form the highest cliffs beneath the Watchman and on Sentinel Point.

The rise of Mount Mazama took place during the Pleistocene period, and as the volcano grew its flanks were mantled with glaciers. Accordingly, the lavas are interbedded in many places with glacial moraines and fluvioglacial sands, and elsewhere there are signs of strong glacial erosion between successive flows. Strangely enough, the flows that were erupted onto and under the glaciers show no peculiarities suggestive of rapid chilling. Moreover, there must have been recurrent mudflows on the sides of the volcano as the ice was melted by falls of ash and eruptions of lava, yet no deposits of such flows have been recognized on the walls of Crater Lake. They must have been swept to lower elevations and buried there by later ejecta.

### INTERBEDDED ANDESITIC PYROCLASTIC ROCKS

Although the tuffs and breccias on the walls of Crater Lake are largely masked by talus, the tendency has been to exaggerate the amount of explosion debris. This tendency is easily explained, for it is only on close inspection that most of the red and brown layers between the lava flows, which seem at first sight to be of explosive origin, are seen to be merely the oxidized tops and bottoms of flows. Possibly the autobrecciated bases of many flows have also been mistaken for pyroclastic breccias.

Layers of pyroclastic debris are most abundant on the south and southeast sides of the caldera. Varicolored, coarse tuff breccias may be seen to advantage on the cliffs below the Sinnott Memorial, where they form more than half of the caldera wall. A convenient place to study similar fragmental ejecta is on the trail to Garfield Peak, where one of the layers of tuff breccia is 100 feet thick and carries blocks of andesite up to 6 feet in diameter in a matrix of solfatarized tuff. The bold face of Eagle Crags is striped with many thinner bands of similar ejecta; so also is the slope leading from Applegate Peak to Sun Notch. It must be emphasized, however, that these layers of pyroclastic material thin rapidly as they are traced away from the caldera rim. A mile or two away only a few thin bands persist. The inference is, of course, that the explosions which produced them were not particularly violent.

No part of the walls of Crater Lake is more impressive than the tremendous Dutton Cliff, which rises almost 2000 feet above the water. Here the somber lava flows are separated by brown and brick-red layers, mostly a few feet thick though reaching a maximum thickness of more than 80 feet, which seem at first sight to be coarse tuff breccias. Careful study shows that all but a few of these brighter layers are the slaggy, autobrecciated tops and bottoms of the flows themselves. It is enough to see how the lavas grade imperceptibly into the breccias and to note how they send irregular fingers upward into them to be convinced that these are not breccias of explosive origin, but a product of quick chilling and subsequent shattering of lava crusts.

True explosion breccias are not lacking on Dutton Cliff, but they are readily distinguishable by reason of their stratification and depositional relations to the lavas beneath. The most conspicuous of these pyroclastic bands is one composed of pale sage-green tuff breccia, which reaches a thickness of 50 feet in places and carries angular blocks of andesite up to 3 feet across. It outcrops a short distance below Sun Notch and continues thence eastward toward Kerr Notch, as shown in plate 6.

Farther down Dutton Cliff, and on Phantom Ship, pyroclastic deposits are more abundant. These are products of the Phantom cone and have been discussed already (page 30).

Coarse, red agglomerates and breccias occur as irregular lenses between the lavas above Danger Bay, but between Sentinel Point and Pumice Point pyroclastic deposits are both rare and thin. In the lower part of Pumice Point, however, there occurs a layer of tuff breccia 150 feet thick. Thin bands of similar ejecta may also be found between the lavas on the walls of Steel Bay and beneath Llao Rock.

From what has been said it may be concluded that although explosive activity continued at intervals throughout the growth of the main cone of Mount Mazama, it was far subordinate to effusive activity. Such explosions as there were must have been principally at a low temperature, the ejecta being blown out for the most part in a solid state as angular blocks in a matrix of ash. True scoria (cinders) and rounded bombs are conspicuously absent; in other words, none of the explosions seems to have been of the Strombolian type, in which the ejecta are blown out while still sufficiently viscous to have their forms modified by flight through the air.

The nature of the pyroclastic deposits provides evidence that the feeding magma chamber or explosion focus lay at shallow depth, for despite a careful search no fragments of the Western Cascade lavas or of the underlying rocks have ever been found among them. Indeed, fragments referable to the older Pliocene lavas beneath Mount Mazama are extremely rare, the ejecta being almost entirely composed of typical Mazama andesites. On other volcanoes in the southern Cascades there is a similar absence of explosion debris from the underlying basement. Presumably the tops of the magma chambers lay close to the surface; that of Mount Mazama may have been well above the level of the Miocene lavas and probably lay among the upper flows of the Pliocene High Cascade basalts. If this inference is justified, it helps to explain why the earlier explosions of Mount Mazama were not especially violent, for magma at shallow depth cannot hold enough gas in solution to cause explosions of great intensity.

### Solfataric Areas and Vents

Much of the beauty of the walls of Crater Lake comes from the delicate coloring of the rocks, notably on Garfield Peak and the Eagle Crags and beneath Hillman Peak, where they have been affected by solfataric action. Here the normally somber colors of the andesites give way to shades of yellow, buff, brown, and orange which contrast pleasingly with the deep blue of the adjacent lake and the bright reds of the slaggy lava crusts. Where the lavas have been attacked by rising gases and solutions, they have been reduced to soft, friable masses of brown "earth" composed chiefly of kaolin and opal stained by iron oxides. Elsewhere, they have been bleached to white masses of opal stippled with crystals of pyrite; or, again, the joint faces of the rotted flows may be lined with films of specular hematite and sulphur. Some lavas assume dull-green and brown tints where the ferromagnesian constituents have been converted to chlorite and limonite. In general, the alterations are more pronounced in layers parallel to the banding, so that fresh flows alternate with others which resemble tuff breccias containing unaltered blocks in a rotted matrix. On the western wall of the caldera, discoloration of the lavas increases toward the conduit of the Hillman cone, indicating that decomposition was caused by emanations issuing from that vent. Finally, judging from the occurrence of abundant chips of opalized and thoroughly oxidized lava among the final ejecta of Mount Mazama, the upper, vanished part of the volcano was also the site of many solfataras and fumaroles.

No doubt most of the andesites in the walls of Crater Lake issued from vents near the summit of the mountain. This much follows from their more or less quaquaversal dips. It must not be thought, however, that Mount Mazama was ever a single, symmetrical cone. The walls of the caldera reveal many angular unconformities that cannot be attributed to erosion, but indicate either that the central vents shifted or that several vents were active simultaneously. Angular unconformities related to glacial erosion are easy to recognize, for there is usually a layer of morainic detritus between the unconformable flows. On the other hand, unconformities caused by the activity of shifting or multiple vents are marked by the overlap of one set of flows on the smooth surface of an earlier set. For example, the broad arch of lavas at the base of the caldera wall below Llao Rock, which represents the section of an old cone, is overlapped by a younger arch of lavas the crest of which lies approximately beneath Hillman Peak, and this in turn is partly overlain by the remnant of a third cone which, like the first, culminates approximately beneath Llao Rock (plate 8). These and similar unconformities suggest that Mount Mazama was a complex of overlapping cones.

The symmetry of Mount Mazama was also destroyed by the activity of glaciers. To judge by the great piles of morainic material on the north wall of the caldera, glacial erosion was most intense on that side of the volcano. We find in this a contributory cause for the fact that the north wall of Crater Lake is so much lower than the opposite wall.

On large composite volcanoes, outflow of lava from the summit vents is commonly augmented by eruptions from fissures on the flanks. All the dacite flows of Mount Mazama issued from such lateral fissures. Even before the period of dacitic activity, some of the andesitic flows escaped from vents far below the summit. Three of these vents are perfectly exposed on the walls of Steel Bay (see panorama, plate 28). The youngest is represented by a dike which emerges from the talus about 100 feet above the lake, where it has a width of approximately 15 feet. Upward it thickens gradually, until it suddenly flares into a flow approximately 100 feet thick. An older vent lies a little farther east. Here lava rose through a fissure that widens from 30 feet near the edge of the lake to more than 80 feet about 300 feet higher. At that level the lava escaped from the fissure onto the surface and spread as a wide flow up to 200 feet in thickness. The third and oldest dike-feeder is exposed near the center of Steel Bay, and though it has a maximum width of only 15 feet it fed an extensive flow more than six times as thick.

Although these are the only lavas traceable to parent fissures, many other thick flows near the caldera rim were probably erupted from lateral openings. Some of these are described in detail in the section dealing with the Northern Arc of Vents.

## Dikes

After Mount Mazama had grown to considerable height, its sides were split by more or less radial fissures, partly as a result of the weight of magma in the central conduits but mainly in response to a general doming of the entire volcano by increased pressure of magma in the underlying reservoir. The fillings of at least sixteen of these fissures are exposed as dikes on the caldera walls. Other radial fissures underlie the outer flanks of the volcano and the region beyond, where they served as feeders to many of the parasitic cinder cones and dacite domes. Considering the former size of Mount Mazama and the extent of the caldera walls, the number of exposed dikes is surprisingly small as compared with the number visible on many smaller volcanoes.

With the exception of two dikes of dacite, all are composed of andesite similar to that of the flows which they cut.

### *Dacite Dikes*

Almost immediately beneath the central part of the dacite flow forming Llao Rock, there are two small dikes of dacite. Diller maintained that one or possibly both contributed to the escape of the Llao lava, but of this there is no proof. Neither intrusion can be seen to connect with the flow, and it seems more likely that both dikes and flow were supplied from a common feeder.

Of the two dikes, the more westerly varies between 6 and 7 feet in width. Approximately 60 feet above the level of the lake it disappears. The margins of the intrusion consist of jet-black glass, but the interior is pale gray, holocrystalline, and well banded. Slender prisms of hornblende and stumpy laths of plagioclase are scattered throughout, and minute spheroids of cristobalite line cavities in the pale interior.

The other dike (plate 7, figure 2) follows a sinuous course across the caldera wall and can be traced to within approximately 150 feet of the base of the Llao flow. For most of its course this dike measures between 4 and 5 feet in width, but at the top it diminishes to a width of 3 feet 6 inches. The margins consist of black obsidian. Within, the dacite first becomes holocrystalline, pale gray, and almost pumiceous, and then, in the center, becomes darker, less vesicular, and strongly banded. In the same direction, the content of cristobalite increases. Similar variations may be noted in the Llao flow.

### *Andesite Dikes*

Of all the dikes on the walls of Crater Lake, only one, the Devil's Backbone, reaches from the water's edge to the rim. If this once served as the feeder to a surface flow, the lava has been removed by erosion. Close to the lake the dike is 23 feet wide, but upward it increases in width to approximately 50 feet. Slightly more than halfway up the caldera wall, the dike is offset (plate 29). Like the dacite intrusions just mentioned, the Devil's Backbone has thin glassy selvages enclosing a paler, holocrystalline, and somewhat vesicular core rich in cristobalite.

Perhaps the most interesting of all the intrusions are those on the walls overlooking Steel Bay, under the east "wing" of the Llao flow. These, as indicated already (page 34), represent feeders of surface flows.

On the cliffs overlooking Grotto Cove, a dike with glassy, vesicular borders can be traced upward from the edge of the lake through a vertical distance of approximately 200 feet. Throughout this distance it maintains a width of 10 to 15 feet. Close to the top, on its western face, the margin includes a few reddened glacial boulders a foot or so in diameter.

Two conspicuous dikes cut the lavas on the walls immediately south of the great V-shaped dacite flow forming Redcloud Cliff. These are shown on the panorama, plate 23. The larger dike, which has a width varying between 6 and 8 feet and descends almost to the edge of the lake, has glassy margins, but its interior is composed of normal pilotaxitic hypersthene andesite.

About halfway between the center of Cloudcap Bay and Sentinel Point there is another conspicuous wall-like dike of andesite with glassy margins. On Sentinel Point itself, a similar dike descends to the water's edge. At that level its width is 25 feet, but upward it breaks into two thinner branches. The margins of this dike are glassy, but the core is crystalline and vesicular and carries many basic inclusions.

Phantom Ship consists of pale-green lapilli tuffs and tuff breccias cut by two branching, more or less vertical dikes of dense, black andesite. The pyroclastic rocks are part of the old Phantom cone, and the dikes appear to be radial with respect to the central conduit exposed on the adjacent Dutton Cliff. The larger dike forms most of the northwest half of the island and is responsible for several of the sail-like pinnacles of the "ship." Apparently the dikes were intruded after the enclosing tuffs had suffered extensive alteration, though the concentration of hematite along cracks cutting the margins of the dikes shows that the intrusions themselves suffered attack by fumarolic vapors.

Below Sun Notch there is a dike of olivine-bearing hypersthene andesite, 6 to 8 feet wide, which reaches almost to the rim of the caldera. Thirty feet from the point where it disappears beneath the talus, the dike splits into two parts, each about 5 feet wide. Both parts consist of black, glassy lava devoid of basic inclusions.

An unusually long dike cuts the Eagle Crags near Garfield Peak, descending from a point not far inside the rim to the edge of the lake, more than 1200 feet below. On account of the solfataric alterations to which this intrusion has been subjected, a fuller account is given in the section dealing with petrography (page 145).

Finally, a similar dike, trending almost east-west, is traceable throughout the greater part of the caldera wall immediately west of the trail leading to the boat landing.

# Mount Scott

During the later stages of the growth of Mount Mazama a large parasitic cone developed not far above its eastern base. The remains of this cone form Mount Scott, the highest peak within the park, a landmark visible for tens of miles. Viewed from the east (plate 9, figure 2), Mount Scott still shows the form of a symmetrical truncated cone, but seen from other directions it is markedly asymmetrical, chiefly because much of its northwest side has been destroyed by the development of a large glacial amphitheater (plate 9, figure 1).

The first feature that arrests attention is the steepness of the cone. Considering that the slopes are composed almost entirely of lava flows, they are surprisingly steep. The dips of the lavas commonly range between 20° and 30°, and locally they even exceed the larger figure. On the walls of Crater Lake the dips of the lavas are only a third or a quarter as steep.

There is no trace of a summit cinder cone on Mount Scott. The attitudes of the lavas show that the vent lies on the wall of the cirque, approximately ⅓ mile west of the summit, where it is concealed beneath the talus. The original limits of the cone can only be guessed at, for all the contacts with the lavas of Mazama are buried by pumice. Certainly none of the lavas exposed on the walls of Crater Lake came from Mount Scott. In that direction, the flows did not spread more than a mile from the vent. In other directions the Mount Scott lavas were able to move farther. Eastward, they pass beneath flows and domes of later dacite.

Mount Scott must have become extinct long before the last explosions of Mount Mazama. Probably it had even ceased to erupt before the dacites of Llao Rock, Cleetwood Cove, and Redcloud escaped from the Northern Arc of Vents. Its growth may therefore have been confined to the Pleistocene period.

The lavas of Mount Scott do not differ materially from the principal flows of Mount Mazama. They are pyroxene andesites rich in phenocrysts of feldspar, and carry plentiful basic inclusions. Some flows are distinctly glassy; others are dull and lithoidal. Interbedded with them are layers of coarse tuff breccia charged with angular blocks, apparently products of low-temperature explosions.

Conspicuous signs of solfataric action may be seen on the western wall of the cirque and bordering the trail near the summit. Here the rocks are thoroughly decomposed, either to masses of milky opal and kaolin or to brownish limonitic aggregates. Locally the lava surfaces are coated with brick-red iron oxides and small patches of specular hematite, and occasional joints and vesicles are lined with tridymite sublimated from acid vapors.

# The Earlier Dacite Eruptions

For convenience in description, the dacites of the Crater Lake region may be divided into three series. The youngest includes the vast deposits of dacite pumice erupted just before the formation of the caldera. An older series includes deposits of pumice and viscous domes and flows erupted from a semicircular arc of vents on the northern flank of the volcano; to this series belong the lavas of Llao Rock, Cleetwood Cove, Grouse Hill, and Redcloud Cliff. The third and oldest group of dacites includes the dacite pumice interbedded with andesites on the caldera walls, together with the extensive sheets of dacite lava and dacite domes on the south and east slopes of the volcano. In this section, only the third group is to be discussed.

Before any of these eruptions of dacite began, Mount Mazama was already a giant andesitic cone, and had almost attained its maximum height. Mount Shasta had likewise reached its greatest elevation before dacites commenced to escape from fissures far down its sides. Moreover, the only dacitic material erupted from the summit of Mount Mazama was in the form of pumice; the dacite flows and domes all issued from subterminal fissures.

### The Southern Dacite Flows and Domes

Probably the first dacites erupted by Mount Mazama were those forming Grayback Ridge and those making up the southern end of Vidae Ridge. After eruption, they were almost completely buried by glaciers which choked and overflowed the canyons of Sun, Sand, and Annie creeks. The lavas therefore date back to a time preceding the maximum glaciation of Mount Mazama. On the other hand, the younger flows of dacite erupted from the Northern Arc of Vents belong to a much later period when the great valley glaciers had dwindled to small tongues extending only a short distance beyond the present rim of Crater Lake.

The dacites of Vidae and Grayback ridges can be followed up the slopes of Mount Mazama to an elevation of slightly more than 6500 feet. At Tututni and Maklaks passes they disappear. Unfortunately, their relation to the neighboring andesites at those points is masked by glacial drift. They can never have extended farther up the sides of the volcano, however, for if they had they would be exposed on the sides of Dutton Ridge and Vidae Ridge. Neither there nor on the walls of the caldera is there any trace of them. Accordingly, they must have escaped in part from fissures close to Tututni and Maklaks passes.

Southward from the probable vents, the thickness of the dacites increases rapidly. A mile away, both the Grayback and Vidae lavas reach a thickness of 500 to 600 feet. The Grayback flows continue to thicken until, close to the southeast corner of the park, their thickness approximates 1000 feet.

Not all this dacite issued from fissures at Tututni and Maklaks passes; much was erupted from vents scattered along the length of the flows. Flow for flow, the dacites are much thicker than the andesites which make up the primary cone of Mount Mazama. In the cliffs south of Maklaks Pass there is an unbroken sheet of glassy dacite 500 feet thick, apparently the product of a single eruption. On the opposite side of Sun Creek canyon, near Tututni Pass, one of the flows is at least 200 feet thick.

Other features serve to distinguish the dacites from the older andesites of Mount Mazama. Many of them were formerly so much more glassy that they may properly be spoken of as devitrified obsidians. Coupled with this former glassiness are a delicate, hair-fine banding never seen among the andesites, and an abundance of glistening plates of tridymite lining lithophysae and joint planes. Some of the flows are heavily charged with pink and gray spherulites up to an inch in diameter; in others, dense blue-gray bands alternate with highly pumiceous cream and white bands. Phenocrysts of quartz seem to be absent, but large crystals of feldspar and granules of pyroxene are ubiquitous. Noteworthy also is the fact that by

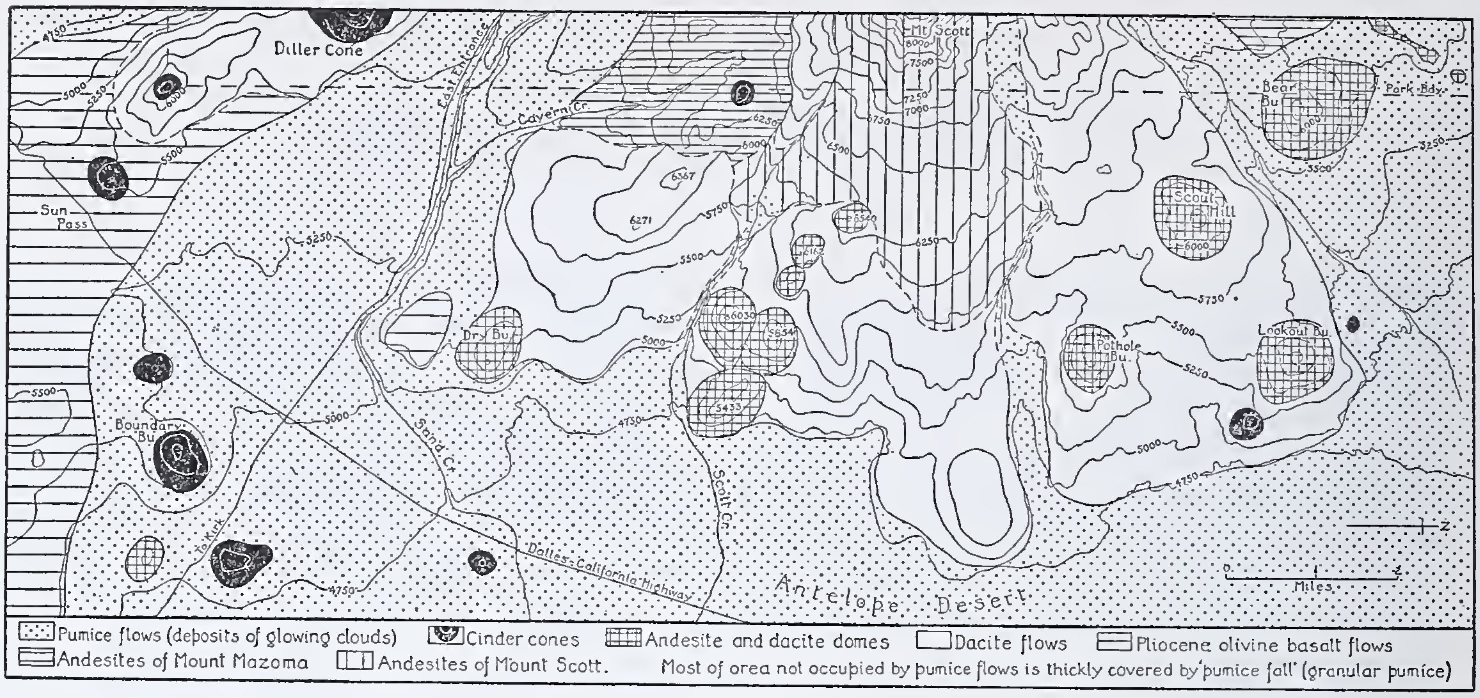
Diller Cone
Mt. Scott
Bear Bu.
Park Bdy.
Sun Pass
Cavern Cr.
Scout Hill
Dry Bu.
Pothole Bu.
Lookout Bu.
Boundary Bu.
Sand Cr.
Scott Cr.
Dalles-California Highway
Antelope Desert
Miles
N
Pumice flows (deposits of glowing clouds)
Cinder cones
Andesite and dacite domes
Dacite flows
Pliocene olivine basalt flows
Andesites of Mount Mazoma
Andesites of Mount Scott.
Most of area not occupied by pumice flows is thickly covered by "pumice fall" (granular pumice)

Fig. 6. Map of the region east of Crater Lake National Park

comparison with the andesites they are much poorer in basic, lamprophyric inclusions. Finally, the banding in the flows commonly steepens upward from the base and inward from the margins, so that near the top it may be vertical.

Several oval hills rise above the general level of both Vidae and Grayback ridges. Examples are those numbered 5725, 6122, and 6077 on the geologic map (plate 3). Some are entirely buried by pumice and glacial drift, and even on the others exposures are rare. Probably the tops of the highest hills were never covered by ice. These hills are not simply erosional remnants of lava flows; they seem rather to represent domical protrusions of Pelean type, and they may be the final products of vents from which some of the dacite flows were erupted. Each hill consists of pale-gray or white pumiceous dacite, either obscurely banded or quite devoid of fluxion, so that the internal structure cannot be determined. On some, the surface is littered with round boulders of tridymite-rich, crumbly dacite, reminiscent of the blocky crusts of Pelean domes seen in other volcanic regions.

## The Eastern Cluster of Domes and Flows

At the eastern foot of Mount Scott, and extending thence downward to the plateau bordering the Dalles-California highway, there is a remarkable group of domes. In an area of approximately 25 square miles, a dozen or more steep-sided symmetrical buttes may be seen, and the geologist, viewing them from a distance, might well be pardoned if he mistook them for basaltic cinder cones (plate 9, figure 2). They are, however, protrusions of Pelean type.

Several of the protrusions, such as Lookout, Pothole, and Dry buttes, stand isolated on platforms of dacite, but most of them, as figure 6 shows, occur in clusters. A few seem to be arranged along fissures which are radial with respect to the cone of Mount Mazama, but the majority show no systematic alignment. Those within or close to the park boundary appear to be a little older than those at lower elevations, though none seems to have suffered from glaciation. Indeed, the perfection of their forms and the steep fronts of the lava flows associated with them indicate that they are among the latest manifestations of activity at Mount Mazama prior to the destruction of its summit. There is no accurate criterion by which to judge their age with respect to the dacites erupted from the Northern Arc of Vents, such as the Llao Rock and Cleetwood flows, but from the degree to which they have been eroded it seems safe to say that they are not much older.

The eastern domes range between ½ and 1 mile in diameter, and between 500 and 1000 feet in height. The southernmost, Dry Butte, consists of hornblende andesite, but the others are chiefly composed of friable, almost pumiceous gray pyroxene dacite, like the associated flows.

On most of the domes, solid outcrops are restricted to the topmost crags and even in these there is usually too little flow banding to suggest the internal structure. On 5433 Hill, however, the crags on the south side show that near the base the banding generally either is flat or dips inward at low angles; higher up the banding steepens, and at the top it is commonly vertical. In other words, the banding on this dome is crudely fan-shaped. On Lookout Butte also, the summit crags exhibit steep flow planes. Pothole Butte may represent a domical protrusion that rose from the vent through which the underlying flow of dacite was erupted. The relations here recall those to be described on Grouse Hill (page 49). The line of small buttes immediately northwest of Bear Butte represents three distinct protrusions along a common fissure directed toward the central vents of Mount Mazama.

Approximately 4 miles southeast of this large cluster of domes, and close to the base of Boundary Butte, there is an isolated hillock of dacite, sometimes referred to as Egan Spring Butte (figure 6). A thick blanket of pumice makes it impossible to determine the internal structure. The surface, however, is littered with large subangular blocks of vesicular dacite. Presumably, therefore, the hillock represents another small domical protrusion. Judging solely by its form, it seems to be of about the same age as Boundary Butte and the other basaltic scoria cones not far away. If so, basic and acid magmas were erupted from closely spaced vents in quick succession.

# Inter-andesitic Dacite Pumice on the Caldera Walls

In this section, our concern is with the deposits of dacite pumice erupted during the closing stages of the andesitic period in Mount Mazama's history and before the extrusion of the dacite flows from the Northern Arc of Vents; in other words, before the flows of Llao Rock, Cleetwood, Redcloud Cliff, and Cloudcap.

On the south wall of the caldera, the dacite pumice in question is restricted to a single small lens, approximately a third of the distance down the wall, ¼ mile north of Discovery Point. On account of its pink color, it is plainly recognizable even from a distance, and can be traced laterally for several hundred yards. The maximum thickness is close to 30 feet. Locally the pumice rests on andesitic lava, but generally it is underlain by coarse, bouldery till. Above it lie two thick flows of andesite separated by glacial debris. Capping the highest flow are two other layers of dacite pumice separated by till; these, however, belong to the post-andesitic activity of Mount Mazama.

Between Discovery Point and Redcloud Cliff, inter-andesitic pumice seems to be absent. The thin lenses under the moraines in Sun and Kerr notches belong to a later time, and the topmost pumice on the caldera rim is a product of the culminating explosions of the volcano. Below the dacite flows of Redcloud and Cloudcap, however, dacite pumice and welded tuff are exposed to a thickness of approximately 200 feet (plate 10). Their pale cream, buff, and pink colors contrast strikingly with the dark lavas above and below. The eye is also attracted by them on account of the fantastic forms into which they have been eroded, especially at the Cottage Rock.

The section at Cottage Rock (see figure 7) is as follows, the series beginning at the top:[1]

*a.* The Cloudcap dacite flow.

*b.* Welded dacite tuff, similar to that of the Wineglass (page 60); 20 feet. This deposit is rich in angular blocks of andesite, and upward merges imperceptibly into the Cloudcap lava.

*c.* Pink and brown lump pumice; 3 feet.

*d.* Block layer consisting chiefly of lithic fragments of andesite in a matrix of dacite pumice; 4 feet.

*e.* Compacted, but not welded, pink and brown lump pumice crowded with fragments of andesite; 3 feet.

*f.* Well bedded, smoke-gray lump pumice with lithic blocks up to 2 feet across forming a fifth of the whole; 70 feet.

*g.* Uncompacted red, pink, and brown lump pumice with fewer lithic blocks; 50 feet.

*h.* Welded and streaked, red and black dacite tuff (ignimbrite), similar to the Wineglass tuff; 6 feet. This forms the conspicuous dark band at the base of Cottage Rock itself.

*i.* Unwelded, but compact, pink and brown lump pumice; 30 feet.

*j.* Strongly welded red, brown, and black tuff; 3 feet.

*k.* Buff and white, incoherent lump pumice with abundant lithic fragments; 10 feet.

*l.* Poorly exposed and doubtful glacial till; 10 feet.

*m.* Many flows of andesite, the four lowest of which are separated by layers of till.

Between Cottage Rock and the great V-shaped cliff of Redcloud, the deposits of dacite pumice are divided by a wedge of andesitic lava, as they are in the sections at Pumice Point, Cleetwood Cove, and Llao Rock. The presumption is, therefore, that all these pumice deposits belong to the same general period of transition in Mazama's history, before the eruption of intermediate magma finally gave way to eruption of dacite flows and basaltic scoria.

Many interesting problems are raised by the pumice and tuff deposits of the Cottage Rock section. Eruptions adequate to form 200 feet of ejecta on the caldera walls must of course have laid down a thick sheet over most of the volcano. Yet no corresponding deposits can be identified with certainty on the outer slopes. Possibly the coarse ejecta in Pumice Flat, near

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[1] The writer is grateful to Ranger-Naturalist Wayne E. Kartchner for aid in measuring this section.

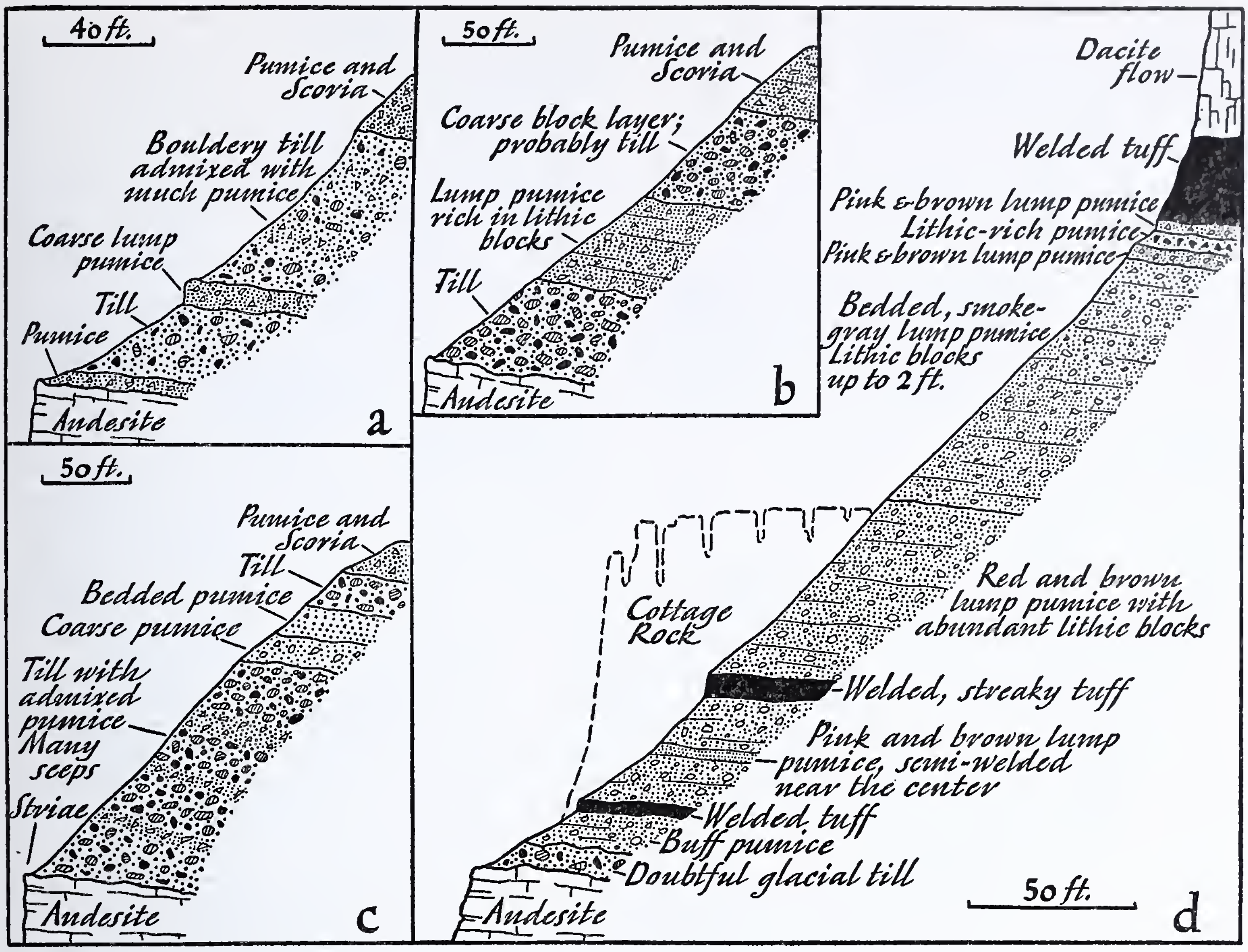

FIG. 7. Sections on the caldera wall: *a,* rim section 150 yards south of Llao Rock dacite; *b,* rim section on trail to top of Sentinel Point; *c,* rim section 150 yards south of the Devil's Backbone; *d,* Cottage Rock section, Redcloud Cliff. Vertical scales exaggerated.

the base of the Union Peak volcano, are of the same age. Certainly they are not products of the final eruptions of Mount Mazama, for the winds at that time were blowing in the opposite direction.

The uncompacted and well stratified lump-pumice deposits of the Cottage Rock section presumably settled from the air in showers. On the other hand, the welded tuff which alternates with them must have been erupted in quite a different fashion. Had these ejecta been thrown high above the vents, they would have lost much of their heat and gas before reaching the ground, and therefore would not have suffered the intense compaction which now characterizes them. So firmly are the constituent particles welded together, and so finely laminated is the tuff, that only microscopic examination permits one to say with certainty that the deposits are not streaky flows of dacite obsidian. In order to produce compaction of this character, the ejecta must have remained hot and gas-rich for a considerable time. Fortunately, detailed study of similar deposits from other regions supplies an answer to the problem. These welded tuffs are products of glowing avalanches (*nuées ardentes*). Even so, it may be asked, how could they have retained their heat and gas long enough to cause welding when two of the layers are only 3 and 6 feet thick, respectively? The answer is, not that they were formerly much thicker, but that they were immediately buried by coarser lump pumice falling from the air. While some of the ejecta rushed down the slopes of the volcano in the form of glowing clouds, the bulk was shot high above the craters and probably fell onto the avalanches soon after they came to rest. The topmost welded tuff, though much thicker, also seems to owe its compaction to rapid burial, for it appears to have been covered immediately by a thick flow of lava.

No inter-andesitic dacite pumice occurs on the caldera walls between Redcloud Cliff and Cleetwood Cove. Beneath the Cleetwood dacite, however, pumice is again well developed. In the conspicuous white slide on the west wall of Cleetwood Cove (plate 26), the measurable thickness approximates 150 feet, and if the deposits continue beneath the talus to the edge of the lake, their total thickness must approximate 250 feet. The topmost 60 feet, immediately beneath the Cleetwood lava, consists of well bedded pumice charged with blocks of andesite up to 3 feet in diameter. By contrast, few of the pumice lumps measure more than 3 inches across, and the majority are not even ½ inch in diameter. Beneath this block-rich layer lies a thick accumulation of equally well stratified but finer pumice in which the content of andesite fragments is much less. A thin wedge of andesitic lava partly separates the two types of pumice, and for a depth of 6 feet the older pumice has been reddened thereby. Three other tongues of andesite are interbedded with the pumice near the base of the slide. The record of events here is therefore as follows: first, alternating eruptions of andesitic lava and fine dacite pumice; then increasingly violent explosions of pumice during which great quantities of andesitic debris were torn from the walls of the vents; and finally, the extrusion of the Cleetwood dacite flow. Had the pumice been blown from the vent which erupted the Cleetwood lava, the dips of the bedded pumice would radiate from the center of Cleetwood Cove. Actually, they conform with the dips of the interbedded andesites and suggest a common source near the summit of Mount Mazama.

On the opposite wall of Cleetwood Cove, inter-andesitic pumice is poorly exposed, outcropping just below the Cleetwood dacite to a thickness of only 35 feet (plate 26). Judging by the abundance of pumice in the talus below, however, there may be a thick series of similar ejecta reaching to the edge of the lake.

The next important exposures of inter-andesitic pumice may be seen in the upper part of Pumice Point, where they form a bold, white face (plate 11, figure 1). The lower half of the point consists of andesitic flows and breccias. Resting on the glaciated crust of the topmost lava is a thin and irregular lens of bouldery till and glacial sand. Above this is 47 feet of coarse lump pumice mixed with large blocks of andesite. After these ejecta had been laid down, they were partly buried by a thick flow of andesite. Both the lava and the pumice were then overridden by ice and a second layer of glacial till was deposited. The ice subsequently retreated, and a dark soil bearing plentiful remains of decayed vegetation accumulated on the moraines. Renewed explosions of dacite pumice then took place, probably from vents at or near the summit of Mount Mazama. These continued until between 130 and 170 feet of ejecta buried the old soil (figure 8). There must have been many explosions of varying intensity, for the deposits are well bedded and differ markedly in coarseness. In some layers the pumice bombs rarely exceed a few inches in diameter; in others they measure a yard across and have pink crusts produced by oxidation of escaping gases. In the finer layers, the fragments of foreign andesite are also small; in the coarser layers, some blocks reach a diameter of 2 feet and they may make up more than a tenth of the whole. Perhaps the rate of deposition and the temperature of the ejecta also varied from time to time, for whereas most of the pumice is white or pale buff and only loosely compacted, certain bands are pink and sufficiently compacted to form small cliffs, as if the ejecta had been hotter, richer in gas, and more rapidly erupted.

Inter-andesitic dacite pumice is again exposed in the upper part of the walls overlooking Steel Bay, where it alternates with lenses of till and flows of andesite (plate 28). Because most of it is concealed by talus and much is difficult of access, the relations have not been determined with the desirable accuracy.

The alternation of andesitic lava with dacite pumice is nowhere more graphically shown than on the caldera walls beneath the east "wing" of Llao Rock (plate 28). Three or four slaggy, red-crusted wedges of andesite may be seen here within a mass of stratified pumice carrying abundant and large blocks of andesite. The maximum thickness of the pumice approximates 300 feet. Above this deposit, and separating it from the dacite flow of Llao Rock, is another stratum of pumice, between 20 and 50 feet thick.

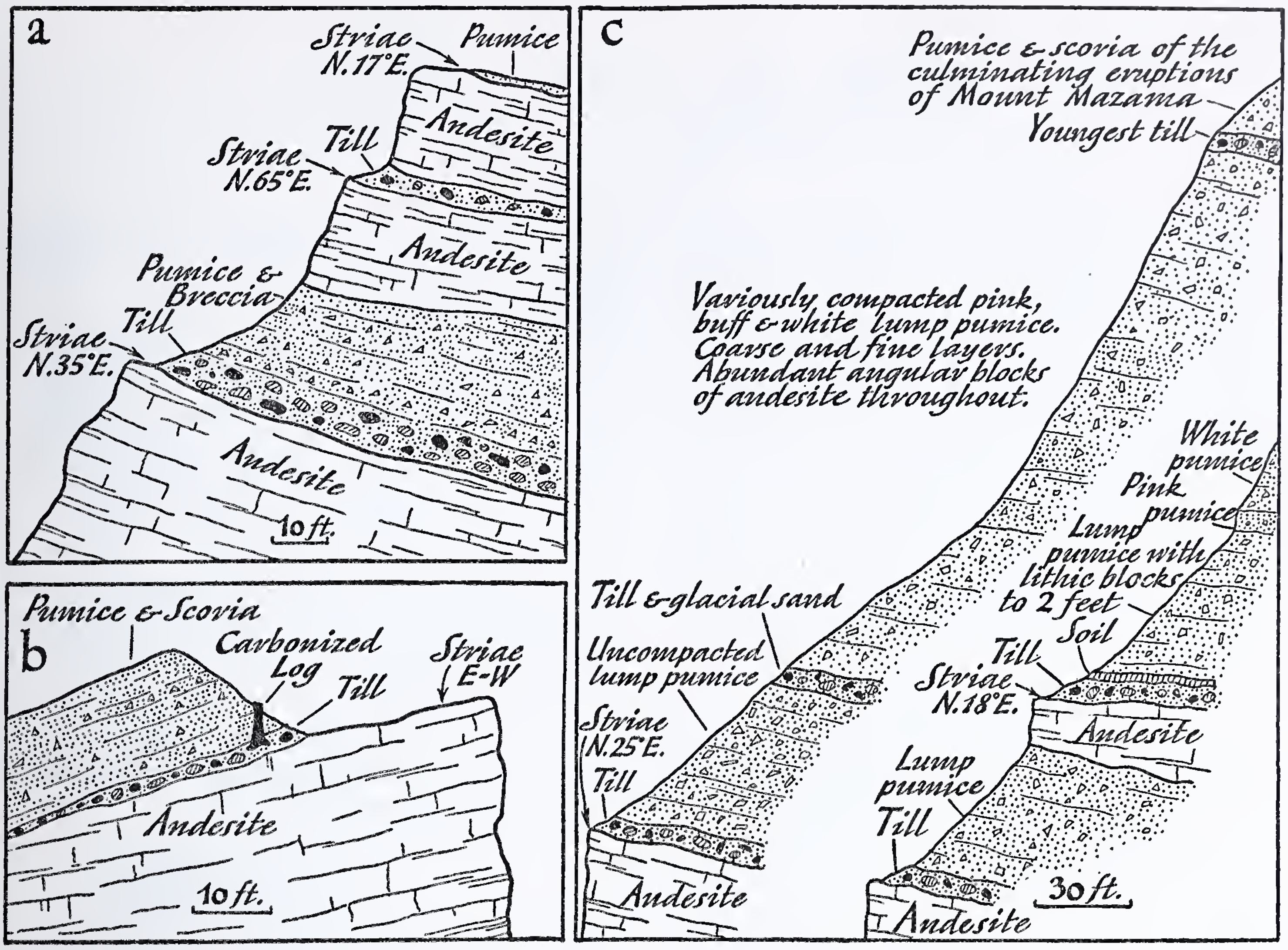

FIG. 8. Sections on the caldera rim: *a,* Glacier Point; *b,* saddle between Discovery Point and the Watchman; *c,* Pumice Point, larger section to west of smaller. (Sections *a* and *b* and part of *c* after W. W. Atwood, Jr., *Journal of Geology,* vol. 43, pp. 142–168, 1935.)

Obviously, a long interval of time elapsed between the eruptions of the two deposits of pumice, for a deep glacial valley was carved across the inter-andesitic pumice before the younger pumice was laid down on the valley side. Probably the older pumice was blown from the central, summit vents of Mazama; the younger pumice, on the other hand, may represent the first products of the vent from which the lava of Llao Rock was extruded.

On the west wall of the glacial valley, the succession is strikingly different from that just described. Instead of a thick series of bedded pumice deposits with lenticular flows of andesite, there are many flows of andesite, a few short and thin lenses of pumice, and at least two layers of bouldery till, the topmost of which forms the floor over which the Llao dacite spread. Both of the observed tills contain much pumiceous debris. Possibly this reworked pumice and the thin lenses of pure pumice associated with it correspond to the thick sheet of pumice on the opposite side of the glacial valley. There is, however, no pumice corresponding to that molded on the east side of the valley. Why the successions on the two sides of the valley are so different is not apparent.

This concludes the account of the inter-andesitic dacite pumice on the caldera wall. Following this period of activity, a semicircular arc of vents opened on the north flank of Mount Mazama, possibly in response to a northward enlargement of the underlying magma chamber.

# The Northern Arc of Vents

The main cone of Mount Mazama had perhaps reached its full height when the centers of principal activity moved from the summit region to the northern flank. When this took place, the glaciers were thin and small and none extended far beyond what is now the caldera rim. Possibly this northward shift of the vents was brought about by enlargement of the magma chamber in the same direction, either as a result of internal assimilation of the cone or, more likely, as a consequence of ring-fracture stoping. Whatever the cause, an arcuate line of vents opened along what later became the north wall of the caldera, approximately 5000 feet below the original summit of Mount Mazama.

It is surely no mere coincidence that the rim of Crater Lake cuts across this Northern Arc of Vents. On the contrary, the position of the rim seems to have been controlled thereby, for the center of Crater Lake does not lie immediately below the former summit of Mount Mazama, but approximately a mile to the north. The eccentricity of the caldera with respect to the main cone appears to have been determined by a predisposing plane of weakness, possibly a continuous ring fracture, the surface expression of which was the Northern Arc of Vents. This eccentric relation accounts in large part for the fact that the north wall of Crater Lake is so much lower than the south wall.

At least six of the Northern Arc of Vents are visible on the caldera walls. In a clockwise direction, these are as follows: the vents of the Watchman andesite, of the andesitic cone forming Hillman Peak, of the Llao Rock, Cleetwood, and Redcloud dacite flows, and lastly of the Sentinel Rock andesite. Possibly another vent lay close to the Wineglass. Possibly, also, such thick flows as those of the Palisades and Roundtop were erupted from vents adjacent to the main arc.

The evidence concerning the exact order of eruption of these vents is incomplete, though the andesitic vents were active before those which erupted dacite. Some of the vents, notably those of Redcloud and Llao Rock, erupted pumice before extruding lava; at other vents, the only activity was the effusion of viscous lava; at Hillman Peak, explosions and effusions alternated many times.

The age of the Northern Arc of Vents relative to that of the other parasitic eruptions on the sides of Mount Mazama is not easy to determine. No doubt the long dacite flows on the south side of the cone, described in an earlier section, are much older, for they were erupted before the period of maximum glaciation. Perhaps the eastern cluster of dacite domes was active about the same time as the Llao, Cleetwood, and Redcloud vents or a little earlier. Most of the basaltic cinder cones must also be approximately coeval, though some may have developed later.

We may now continue to a discussion of the principal vents of the Northern Arc, beginning with those which erupted andesite.

## The Watchman Dike and Flow

Next to the Devil's Backbone, the most conspicuous dike on the cliffs of Crater Lake is the one immediately beneath the Watchman. It stands vertically, forming a high wall cutting athwart the bedded lavas and ashes. Where it disappears beneath the talus, more than two-thirds of the way down the cliffs, its thickness is only about 6 feet, but upward it widens steadily to more than 50 feet and merges into the Watchman flow. There is no difference between the material of the dike and that of the surface lava, both consisting of massive, pale-gray porphyritic andesite. Within the dike, flow banding is obscure, but horizontal and vertical joints are well developed. This is one of the few dikes on the walls of the caldera which do not have black, glassy selvages, the margins being of the same pale-gray color as the interior and no less crystalline. At first sight, the dike seems to represent the actual feeder of the Watchman flow, and it has generally been so interpreted, but a study of the banding in the flow, though not entirely disproving this idea, casts considerable doubt on it. With better reason, the

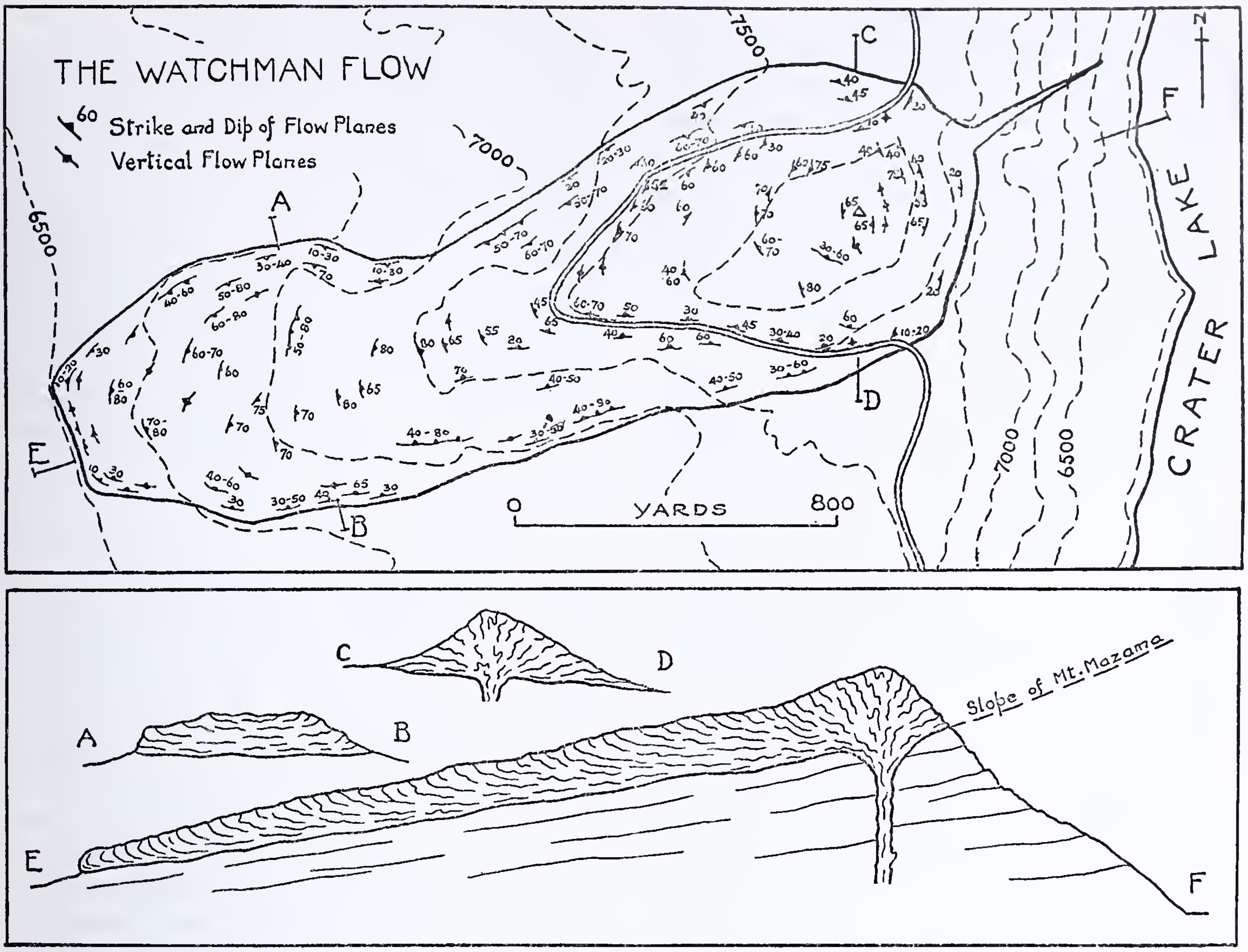

Fig. 9. Map and section of the Watchman flow

dike may be considered as an offshoot from the feeder common to both.

The Watchman flow has a distinct topographic expression, as may be seen in figure 9. Its length is almost 1¼ miles and its average width 2000 feet. The average thickness is between 400 and 500 feet. The flow must have been unusually viscous, for the snout and sides are extremely steep.

Of particular interest is the attitude of the flow planes (figure 9). In general they strike parallel to the margins, and, except in a peripheral belt less than 100 yards wide, they stand either vertically or at steep angles. Even at the snout of the flow the planes still stand steeply and bulge outward in the direction of movement. Along the sides and toward the base, the dip of the planes rapidly diminishes to horizontality. Cross sections therefore show a fan-shaped structure. Under the Watchman itself, the planes are disposed in the form of inverted concentric cones, steeper in the middle and flattening outward. This arrangement suggests an underlying, funnel-shaped feeder. Probably the Watchman, which rises 600 feet above the adjacent rim of the caldera, represents a domical protrusion over the vent.

Although, as we have said, the banding throughout most of the visible part of the flow is vertical and parallel to the margins, it must be assumed that in the lower, unexposed parts it lies at low angles, for otherwise it is impossible to see how the lava could have advanced. Support is lent to this view by study of cross sections of dacite flows on the caldera walls. Apparently the lavas moved somewhat after the manner of glaciers, the upper layers shearing over the lower and turning upward sharply at their distal ends.

Just below and a little to the north of the summit of the Watchman, the lava surfaces are crossed by flutings and scratches which seem at first glance to be of glacial origin. They trend downhill and westward, in the general direction of lava movement. That they are not actually glacial is clear, however, since they may be found in the lee of vertical crags and on the under surface of certain ledges, where ice can have had no erosive power. They must have been caused by frictional drag when the lava had chilled to a solid or semisolid crust.

On many of these fluted faces another curious feature may be observed, namely, streaks of minute hematite crystals. Locally the hematite is concentrated in bands on the crests of the furrows, from which smoke-like trails of hematite dust branch at right angles. Apparently when the separate blocks of lava were pulled apart, fumarole gases made their way along open joints, depositing iron oxide in the initial cavities and then spreading upward as the cracks gaped wider. Elsewhere on the Watchman, hexagonal plates of hematite, up to ¼ inch across, may be found coating joint planes, and much of the brown staining seen on the lavas results from the hydration of this mineral.

The Watchman flow is one of the youngest of the pre-caldera andesites and perhaps coeval with the andesite of Sentinel Rock. Probably it is younger than any of the lavas of the Hillman Peak cone, with the exception of the flow which escaped from Forgotten Crater. It is, however, older than the dacites erupted from the Northern Arc of Vents, for whereas only the lower margins of the dacite flows have been glaciated, all but the highest crags of the Watchman flow have been overridden by ice.

## THE HILLMAN CONE

The highest point on the caldera rim is the summit of Hillman Peak, formerly known as Glacier Peak (see plate 11, figure 2), which rises to an elevation almost 2000 feet above the waters of Crater Lake. Here, as Diller long since pointed out,

> the layers of lava have a decided upward curve when viewed from the lake, and suggest that the volcanic vent from which the lavas of that portion of the rim issued was not central over the lake, but much closer to the western border. This view is fully borne out by the character of the igneous material of Glacier Peak. It is composed in small part of darker slaggy andesites and much red, yellow or whitish fragmental material which is highly colored, as if by the escape of hot volcanic gases near the vent. From the lake these colored patches are brilliant in the morning light.

Clearly, Hillman Peak is the remnant of a parasitic cone on the side of Mount Mazama. When the caldera was formed, the eastern half of the Hillman cone disappeared, revealing a perfect cross section through the central conduit.

In its original state the cone measured approximately ¾ mile across, and it rose to a height of perhaps 1000 feet above the adjacent slopes of Mount Mazama. The lower half of the cone is composed of dark-gray and black "cinders" and scoriaceous tuff breccias (plate 29). The upper part, on the contrary, is made up of dark flows of andesite interbedded with coarse breccias. Much of the lava is kaolinized and propylitized, and some of the fissures are coated with opal and hematite.

In brief, the Hillman cone was built first by explosions of viscous scoria, and later by alternating outflows of lava and more violent, low-temperature eruptions. The flows were confined to the immediate vicinity of the cone, and probably activity came to an end before the Watchman andesite and the neighboring dacites were extruded from the Northern Arc of Vents.

Fortunately, the conduit of the Hillman volcano is perfectly exposed a short distance east-northeast of the summit pinnacle, and is easily accessible. In plan, it is approximately oval, measuring ⅓ by ⅕ mile, and is elongated in a direction more or less radial with respect to the former summit of Mount Mazama (plate 29). Most of the conduit consists of massive andesite devoid of conspicuous banding. Toward the center, this andesite is generally of a pale-gray color, is traversed by widely spaced, steeply dipping joints, and is notably vesicular. Intruded into the pale lava is a denser, darker, and less vesicular andesite in which the jointing is more closely spaced. Similar relations have been noted in the conduits of the Union Peak, Mount Thielsen, and Howlock Mountain volcanoes.

Along the margins of the conduit there is commonly a thin skin of coarse breccia, deeply reddened by the action of gases. Within the conduit are much larger bodies of massive, unbedded breccia, likewise affected by solfataric action. Close to the exposed top of the conduit, near the western edge, the unbedded breccias pass upward gradually into well stratified ejecta that were probably laid down at the surface.

The margins of the conduit seem to have offered ready passage for gases and solutions rising from the chamber below. Not only are the rocks of the conduit itself largely altered, but the enclosing lavas are tinted in shades of orange, red, pink, brown, purple, and green by the development of chlorite, hematite, and limonite, or are bleached to whitish, crumbly masses of kaolin and opal.

## The Sentinel Rock Flow and Vent

The Watchman and Hillman vents, just described, lie at the western end of the Northern Arc, and were active before the vents of the Llao, Cleetwood, and Redcloud dacite lavas. At the eastern end of the arc, on Sentinel Rock, there is a third andesitic vent which also seems to have become extinct before the dacitic lavas were erupted. If, as appears to be the case, all these vents are related to a common and continuous ring fracture at depth, the fracture spread northward while the magma below differentiated.

Owing to difficulty of access, the feeder of the Sentinel Rock lava was not closely examined, but its form can be readily seen from a distance (plate 30, figure 2). It is exposed on the south face of the rock, in the cliffs overlooking Danger Bay, as a tilted, lava-filled funnel. As compared with the older andesites forming the lower part of the cliffs, the flow from the Sentinel vent is extremely thick. In its central part, close to the source, the thickness varies between 300 and 400 feet. The flow is also distinguished from those below by the great abundance of basic, pseudo-lamprophyric inclusions. Locally these constitute as much as a quarter of the total volume. They indicate extensive crystallization of magma along the conduit walls prior to eruption, and this in turn may account for the explosive opening of the vent, for the vapor tension in a magma so far crystallized is likely to have been great. The initial explosions blasted the funnel-shaped crater and left in its vicinity a layer of coarse, red tuff breccia. When the Sentinel lava rose through the vent and spread over the breccia, its base was chilled to black obsidian. The remainder of the flow, cooling more slowly, developed a holocrystalline, pilotaxitic texture except at the top, where again it was rapidly chilled and therefore contains much glass. How far the flow extended beyond the caldera rim, it is impossible to say, for in that direction it is completely buried by later ejecta.

## The Dacite Flow of Llao Rock

The thickest sheet of lava on the walls of Crater Lake forms the imposing cliff known as Llao Rock. In striking contrast with the underlying flows of andesite, which are between 20 and 100 feet thick, the dacite of Llao Rock reaches a maximum thickness of no less than 1200 feet. It was erupted into a hummocky glacial valley, approximately U-shaped in cross section, about ½ mile wide and from 500 to 600 feet deep. Not only did the dacite fill this valley, but it accumulated as a broad, domical pile above it and spread across the valley rims. Naturally, where the lava overflowed the valley the thickness was much less than over the center. On the west bank, the thickness is at most 400 feet; on the opposite bank, it is only about half as much. The total width of the flow is slightly more than 1¼ miles, and its volume approximates ¼ cubic mile.

Though the flow is exceptionally thick, it spread little more than a mile beyond the rim of the caldera. This was partly because the slope of the glacial valley was gentle, but mainly because of the highly viscous nature of the flow.

*Source of the flow.* Beneath the lowest part of the Llao dacite on the caldera wall are two thin dikes. Neither dike can be seen to connect with the lava, and it seems unlikely that, being only 5 and 7 feet thick respectively, they could have served to erupt ¼ cubic mile of viscous dacite. For this reason, some have suggested that the lava was erupted from a vent higher up the slopes of Mount Mazama. This theory, however, is also untenable.

Only by scrambling up the cliffs to the base of Llao Rock can the true relations be observed. There is then no doubt that the buttress which projects lakeward at the bottom of the cliffs represents the actual filling of the conduit. In other words, the Llao lava escaped from a vertical-sided vent on the bottom of a glacial

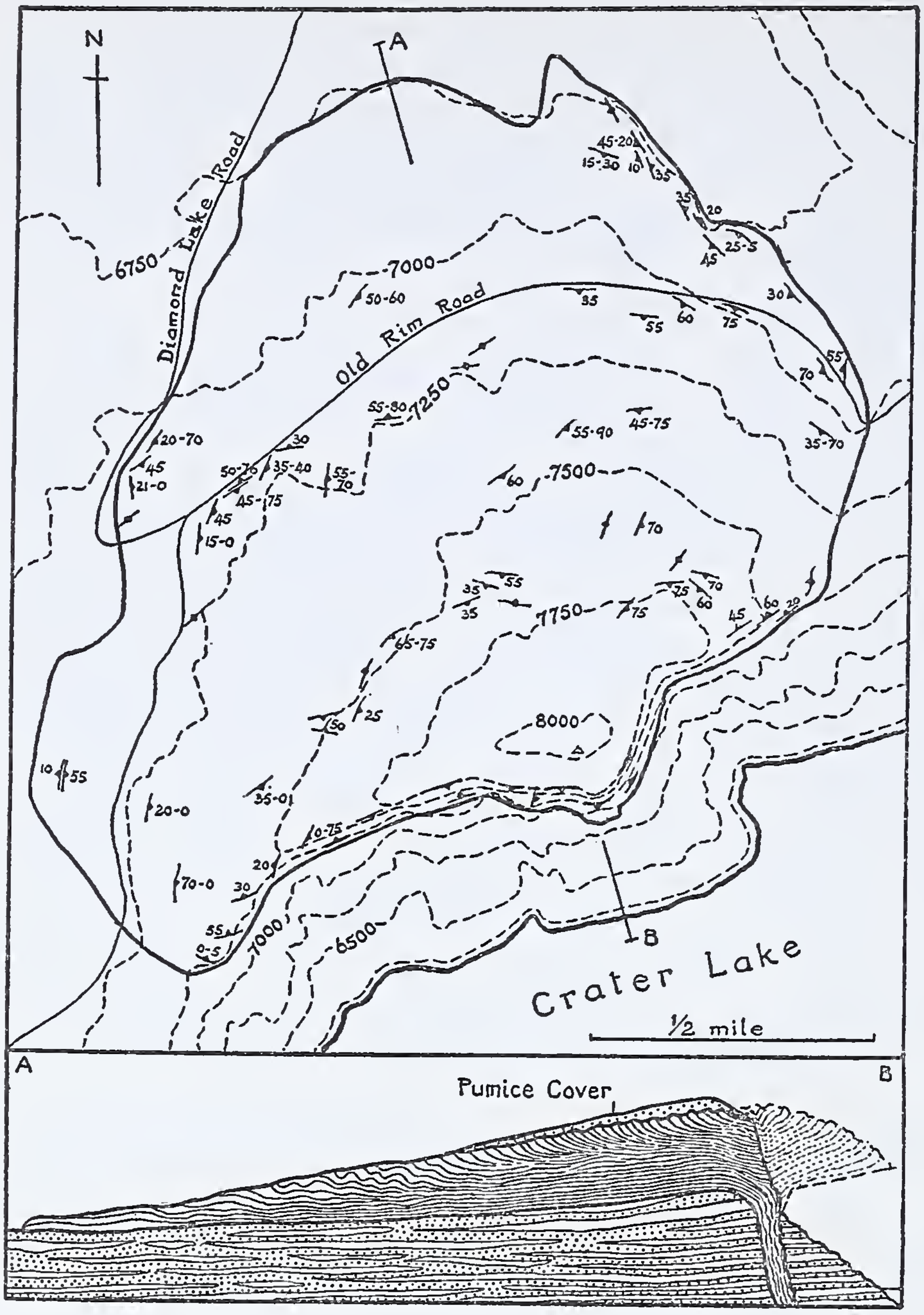

Fig. 10. Map and section of the Llao Rock flow. Map shows the attitude of the flow planes. Where two dip angles are shown, the first refers to the dip at the base of the outcrop, and the second to the dip above. Section shows the position of the feeding pipe, the probable form of the complete flow before the caldera was formed, and the relation of the dacite to the andesites and tuffs below.

valley, several thousand feet below the former summit of Mount Mazama. The photograph (plate 12, figure 1) and the section (figure 10) show the projecting buttress and feeder in relation to the main body of the flow.

*The flow.* The eruption of the Llao dacite was preceded by explosions of dacite pumice. The products of these explosions may be examined on the east side of the glacial valley, where they vary in thickness between 20 and 50 feet. At the base, they are incoherent or but weakly compacted, and consist of coarse lump pumice crowded with angular blocks of andesite. Some of the foreign blocks measure a yard across, but most are less than 6 inches in diameter. Their number is such as to indicate the blasting of a large vent. In its upper part, the lump pumice becomes increasingly compact and welded. Close to the base of the overlying lava it develops such a strong, streaky banding and is so dense that it is difficult to say where the flow begins and the welded pumice ends. Presumably it was the heat and weight of the lava above which caused collapse and welding of the topmost pumice.

If the portion of the Llao lava lost during the formation of the caldera were restored, a large dome would be seen above the vent. The internal structure of this dome would probably be fan-shaped, the flow planes steepening upward and inward. Clearly, the lava can never have extended far toward the south, for its movement in that direction was opposed by the slope of the main cone of Mazama (section, figure 10).

The first lava to escape moved slowly down the glacial valley. Perhaps at an early stage a dome formed above the orifice, and as this continued to grow by expansion from within, the concentric flow bands were disrupted in the central parts and unfolded like the petals of an opening bud. Shortly, the lava filled the old glacial valley and spread onto the surrounding flats.

With a little care, one may examine the flow on the west side. At the base, the dacite is a jet-black glass, streaked in shades of pink and gray. In many places it is highly autobrecciated, and the shattered bottom is rucked up, forming many small caves. Within and just above the blocky basal layer, the flow planes are contorted into flat, recumbent folds, suggestive of viscous drag. Higher up, the contortion rapidly disappears, and the flow planes become smooth and regular. At first they dip into the caldera wall at low angles, conforming to the valley floor; farther up the cliffs, they become horizontal and then gradually the dip changes in direction, becoming increasingly steep and finally, near the surface, becoming vertical.

Beyond the caldera rim, the lava is almost entirely concealed by a blanket of pumice. Clearly, however, the surface of the flow has not been greatly eroded and preserves much of its original form. Only the low fringes of the lava were later covered by ice. The crust must once have bristled with black, glassy spines and turrets and been littered with angular blocks of obsidian. The attitudes of the flow planes (figure 10) resemble those seen in the Watchman, Cleetwood, Grouse Hill, and Redcloud lavas.

When the new highway was made to Diamond Lake, a cave was discovered at the edge of the Llao flow. Allen[1] records that it measures 20 feet long and between 10 and 15 feet in diameter, and that many tributary channels a foot or so across ramify downward from the floor. On the roof of the cave he found abundant specular hematite, some of it in beautiful dendritic forms.

Whereas the basal layer and the crust of the Llao dacite consist chiefly of dense, black obsidian, the bulk of the flow consists of paler, streaky glass which is extremely vesicular and locally almost pumiceous. The rapid alternation of light and dark, that is, of more and less vesicular layers, seems to reflect an unequal concentration of gas within the rising magma.

Reference should be made, in conclusion, to the glacial deposits beneath the lava on the caldera walls. Along the east side of the old valley down which the lava flowed, glacial deposits are absent. The dacite there rests on the coarse lump pumice blown out during the blasting of the vent. Under the west "wing," on the contrary, the lava rests on glacial moraines and fluvioglacial sands (see plate 12, figure 2). Close to the edge of the flow, these deposits approximate 100 feet in thickness and contain much reassorted pumice. Toward the vent they thin, and finally, a short distance down the side of the old valley, they disappear. Striated boulders, up to 18 inches across, occur just below the lava, and occasionally one may find erratics partly embedded in the obsidian, their crusts reddened by heat and escaping gases.

### The Grouse Hill Dome and Flow

A short distance beyond the north rim of the caldera rises the steep-sided and wooded Grouse Hill. Diller supposed that the lava of Grouse Hill was older than the Llao Rock flow, because it seemed to have suffered more from erosion, and because it seemed to be partly overlain by the same sheet of pumice that underlies the great dacite cliffs of Llao. The first of these arguments is questionable, and the second is invalid, for the pumice on top of Grouse Hill is in reality part of the same sheet that lies above the Llao flow. There is, in fact, no way of deciding which of the two flows is the older. Probably they are of about the same age.

*Form and internal structure.* The culminating explosions of pumice from Mount Mazama left a thick sheet of ejecta on top of Grouse Hill. Exposures of the underlying lava are therefore comparatively rare. But the sides of the hill are steep and for long stretches they are almost precipitous. Here, the lava is perfectly exposed and the attitude of the flow planes may be mapped in detail (figure 11). In general, as Allen observed,[2] the banding steepens toward the summit, with the result that, in cross sections, the structure is fan-shaped. Over most of the surface the banding is either vertical or almost so, and it may even maintain this attitude to the edge of the hill. Close to the steep western margin, however, the flow planes commonly dip outward or bulge in that direction. How is this structure to be interpreted?

Grouse Hill may be divided into two parts (figure 11). At the south end there is a domical hill, approximately ¾ mile in diameter. Here the flow planes are arranged in a crudely concentric manner about the summit. To the north lies a mesa, approximately ½ square mile in extent. The flow planes in this area generally trend north-northeast except close to the margins, where they are roughly concentric. Assuming that the lava was poured onto an evenly inclined slope, the thickness in the domical part must be 800

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[1] J. E. Allen, "Structures in the dacitic flows at Crater Lake, Oregon," Jour. Geol., vol. 44, pp. 739–740, 1936.

[2] *Ibid.*, pp. 737–744.

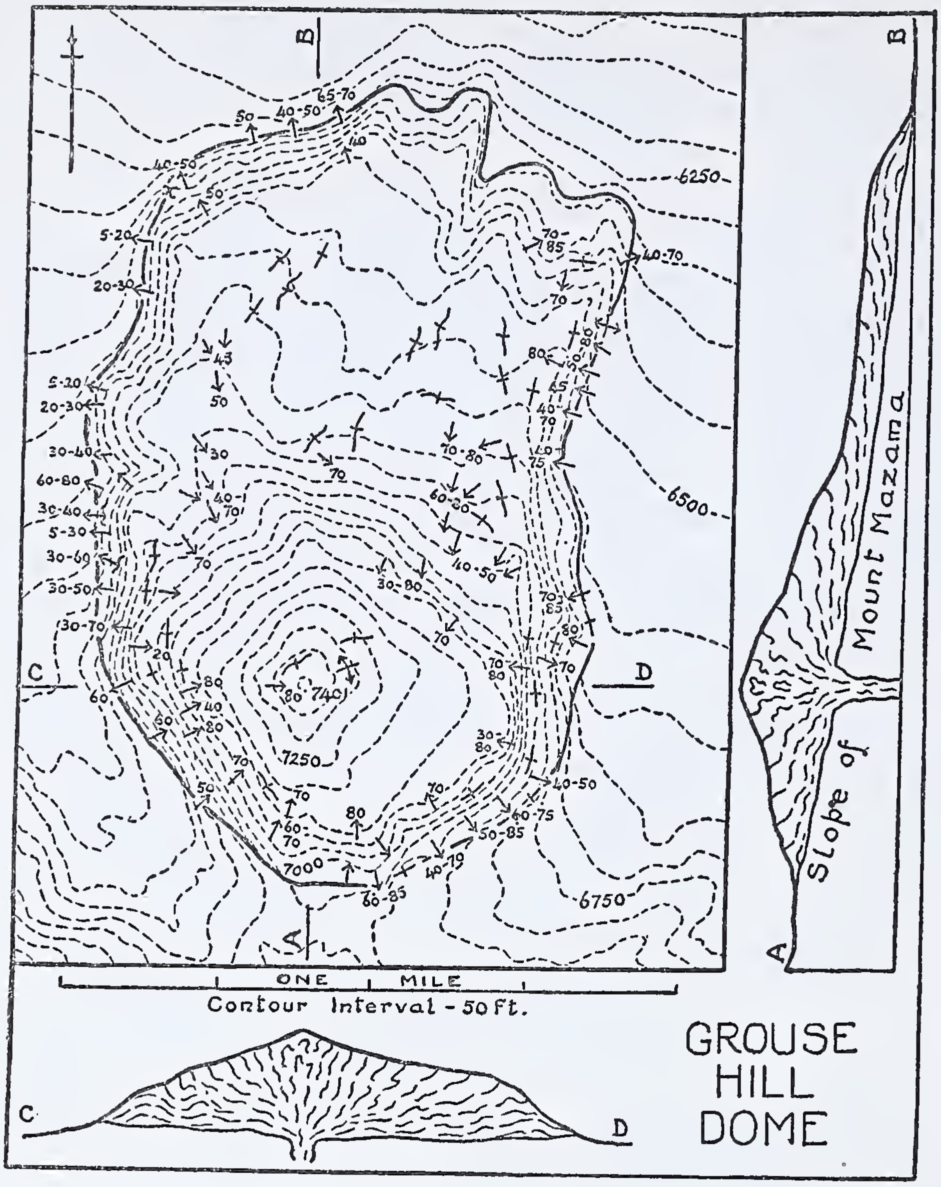

Fig. 11. Map and sections of the Grouse Hill dacite dome and flow, showing the attitude of the flow planes and the probable internal structure.

or 900 feet and in the mesa part about 250 feet. These figures alone are enough to suggest, but coupled with the attitude of the flow planes they clearly indicate, that the vent lies immediately beneath the center of the dome. Apparently the first lava to escape moved sluggishly toward the north, ending in a steep, blocky front. Subsequently the lava became increasingly viscous and accumulated close to the orifice in the manner of a Pelean dome. The total amount of material extruded approximates ⅙ cubic mile.

*The lava.* The dominant lava is a pale-gray, minutely vesicular and glassy dacite, richly charged with phenocrysts of plagioclase, pyroxene, and hornblende. Quartz appears to be absent. In many specimens, glassy and lithoidal layers alternate rapidly, though the distribution of the two types is quite irregular. Strong fluidal banding is almost ubiquitous, and generally it is emphasized by a platy or slabby jointing. As compared with other dacite flows, the Grouse Hill lava is rarely spherulitic and lithophysae are uncommon. Basic inclusions are also scarce, though they seem to be slightly more numerous in the dome than in the flow. Otherwise there is no appreciable difference between the material of the dome and the lava extruded earlier. Streaks of black obsidian, scoriaceous bands, and layers deeply reddened by gas action are scattered at random throughout.

## THE CLEETWOOD FLOW

At Cleetwood Cove, on the north wall of Crater Lake, the stratified lavas and pyroclastic rocks are suddenly interrupted by a dark, jagged tongue of dacite which descends from the rim to the water's edge. The caldera rim, elsewhere fairly smooth, is here so broken by bristling crags of glassy lava as to be called the Rugged Crest.

Diller was much impressed, as every geologist must be, by the fact that the lava forming the tongue on the caldera wall dips lakeward, whereas that on the outer slope generally dips in the opposite direction. This, he thought, added proof to his conclusion that Crater Lake was formed by engulfment and not by explosion, for there seemed to him no escape from the inference that the Cleetwood lava was fluent when the summit of Mount Mazama collapsed. Escaping from a vent near the rim of the caldera, some of the lava moved down the outer slope, while the remainder poured slowly backward into the newly formed depression. Finding no alternative explanation of the supposed "backflow," he was obliged to conclude that the Cleetwood lava was among the final products of Mount Mazama and the youngest of all the dacite flows.

Among the geologists who subsequently paid brief visits to Crater Lake, there were a few who found it difficult to accept Diller's interpretation of the "backflow," and some entertained the idea that faulting on the caldera wall might in some way offer an explanation. Allen, however, was the first to understand the relations correctly. He saw that if the "backflow" is regarded as an "upflow," in other words as the actual feeder of the Cleetwood dacite, all difficulties disappear. The lakeward dip of the lava on the wall does not mean movement in that direction, but exactly the reverse. When the summit of Mount Mazama collapsed, the bounding fracture sliced across the inclined conduit of the Cleetwood flow.

Beneath the flow lies a thick deposit of dacite pumice, interbedded with thin tongues of andesite. The relations are identical with those at Llao Rock, where similar beds of pumice, intercalated with andesites, underlie the great flow of dacite. The low margins of both the Llao and the Cleetwood flows were covered by ice at a later date, but their higher parts remained bare. Presumably, therefore, the two lavas were erupted at about the same time, and long before the catastrophe which produced the caldera.

*The pre-eruption surface.* Before the Cleetwood lava was extruded, there must have been in this vicinity a broad and shallow basin with a hummocky floor. Whether it was cut by ice or by glacial streams is not clear, for wherever the base of the lava is exposed it rests either on andesite or on pumice with no intervening layer of glacial material. Beyond the rim of the caldera, the slope at first was steep and then gradually flattened, the average angle for a mile being approximately 15°. Outward, also, the valley walls diminished in height and soon disappeared. Possibly a corrie glacier had scooped out the depression.

*The feeder.* It is not surprising that in the limited time at his disposal Diller decided that the lava on the caldera wall was a "backflow," for the banding conforms closely to the slope and the rugged, fissured surface suggests a recent flow, frozen in its cascade toward the lake. This appearance, as we have seen, is deceptive. The ruggedness of the surface results from erosion of the lava along joints arranged parallel and perpendicular to the banding, and from the glassy nature of the lava itself.

The contact of the feeding pipe with its walls cannot be seen, though the pipe must widen upward. In general, the banding also becomes steeper in that direction. Close to the lake shore, it lies almost horizontally or dips into the wall at low angles. Higher up, the lakeward dip is generally between 30° and 40°, and where the lava escaped at the surface the banding is vertical or even overturned. In the flow proper, the dips are generally away from the lake, at low angles near the base and at increasingly high angles in the upper parts. Both in the feeder and in the flow adjacent to it, the fluxion planes strike approximately east-west, right across Cleetwood Cove.

There is little difference between the dacite in the feeder and that in the flow. Much of the flow consists of jet-black and dark-gray glass, whereas the feeder is composed of slightly duller and more crystalline dacite, as might be expected considering that it cooled more slowly beneath the surface.

*The flow.* The present area of the Cleetwood flow is a little more than a square mile. Its southern end disappeared when the caldera was formed, but it can never have extended far toward the south, since progress in that direction was impeded by the opposing slope of Mount Mazama. Assuming an average thickness of 300 feet, approximately 1/15 cubic mile of lava was erupted.

Despite its great thickness and volume, the lava was too viscous to move much more than a mile even with the assistance of a 15° slope. On all sides it ended abruptly. Further proof of extreme viscosity may be seen at the base of the flow, where there is commonly a highly brecciated layer up to 12 feet thick, composed of black glass including sporadic blocks from the underlying pumice. Above this basal part rests a layer, averaging 6 feet in thickness, characterized by intensely convoluted flow bands, indicative of viscous drag against the blocky bottom. Above this, in the main part of the flow, the lava is paler and slightly more crystalline; the banding here is no longer contorted, but lies almost horizontally below, then sweeps up to verticality and finally turns over at the surface (figure 12). The crust of the flow, like the bottom, is a glistening black obsidian. The arrangement of the flow bands is thus identical with that seen in the Llao flow.

No feature of the Cleetwood lava is more conspicuous than the ruggedness of its glassy crust. Near the

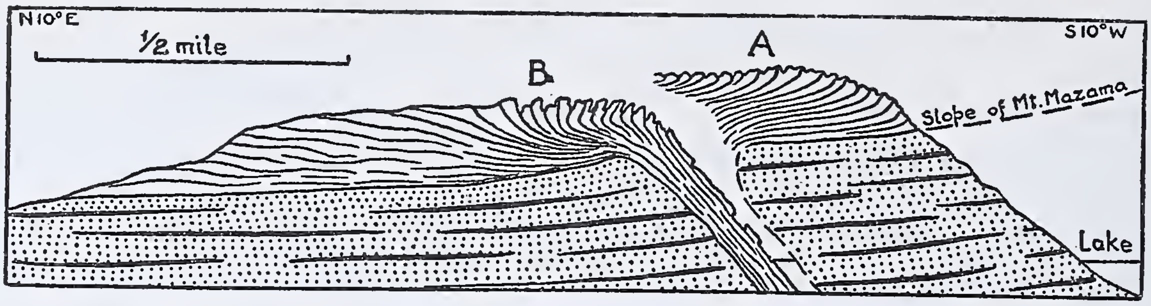

Fig. 12. Section across the Cleetwood dacite flow, showing the internal banding of the flow and its feeder, and the relations to the underlying ejecta of Mount Mazama. Section *A* across the east "wing" of the flow on the wall of Cleetwood Cove; section *B* through the center of the cove.

caldera rim it bristles with pinnacles and jagged spires, some more than 100 feet in height. Bordering the Rim Road, the lava forms a veritable wilderness of crags. These are not arranged haphazard, but in more or less parallel lines separated by gullies, up to 100 yards in width and 150 feet in depth, disposed at right angles to the direction of flow. The gullies seem to be analogous in mode of formation to the transverse crevasses which develop on the surface of glaciers where they plunge over steep slopes. A quarter of a mile beyond the rim of the caldera, the lava becomes much smoother and the gullies disappear, just as the transverse crevasses on a glacier heal and close as the ice moves on to gentler gradients. We may conclude, therefore, that the old slope of Mount Mazama onto which the Cleetwood flow was erupted was much steeper near the point of discharge than farther north. As the stiff lava moved down the steeper slope, the glassy crust was rent by transverse fissures, and the great block ridges were transported on the viscous layers below at different rates. During this motion many of the blocks were tilted so that their banding is now lakeward, in the opposite direction from the banding at the base. Precisely the same phenomenon may be observed on several volcanic domes in Java, notably on Merapi and Soembing. There, viscous lava was protruded onto the sloping floors of craters and continued to pile above the vents until the domes began to slide downhill, leaving in their wake crescentic fissures and lines of crags like those on the Cleetwood flow. The evidence is lost, but it seems permissible to assume that above the feeder of the Cleetwood lava, over what is now Cleetwood Cove, a steep-sided, high dome accumulated, with a fan-shaped internal structure. When the mound of dacite had grown until it became unstable on the sloping floor, the cooler upper part began to slide downhill on the hot lava below.

North of the crevassed area of the flow, farther from the vent, the surface is largely concealed by pumice and scoria, and the scattered outcrops of red, brecciated lava show little fluxion. Along the steep eastern margin, however, the banding is clearly displayed, dipping inward at low angles near the base but steepening inward and upward to verticality. In a few places, the marginal lava shows a gentle outward dip. How closely these structures resemble those seen in the Grouse Hill and Llao Rock flows is apparent from a comparison of figure 12 with figures 10 and 11.

*Nature of the lava.* The interior parts of the Cleetwood flow are normally pale gray and locally almost pumiceous, but the top and bottom usually consist of black obsidian, and it is here that the best development of spherulites and lithophysae may be found. Throughout the mass, fluidal banding is strong, and generally it is emphasized by platy and slabby jointing. On some of the joint faces, particularly at the top of the flow, specular hematite forms a patchy coating. It is also in the higher parts that the lava has been most reddened by escaping gases. As compared with the andesites of Mount Mazama and indeed with most of the other dacites, the Cleetwood flow is poor in basic inclusions. Porphyritic plagioclase is ubiquitous, but quartz seems to be absent; the other phenocrysts are generally hypersthene and red-brown hornblende, augite either being absent altogether or occurring only as microliths in the glassy groundmass.

### Dacites of Redcloud and Cloudcap

The topmost lavas on the caldera wall overlooking Cloudcap Bay are glassy dacites not unlike those of the Llao, Grouse Hill, and Cleetwood flows. They were likewise erupted after the andesitic phase of Mazama's activity had come to an end. Two main flows may be distinguished: an older one to the south, which seems to have had its source beneath Cloudcap, and a much thicker flow farther north, the Redcloud flow, which escaped from a vent on the caldera wall. The relations between them are indicated on the panorama, plate 23.

The V-shaped cross section of the Redcloud lava is hardly less impressive than the great cliff of Llao on the opposite wall of the caldera. In its central part, the lava forms a precipice 600 feet in height. Some who view this massive flow from a distance are inclined to suppose that it poured down a deep, V-shaped river gorge, filling it to the brim and then spreading over the banks. A moment's reflection should, however, dispel this idea. How could a V-shaped canyon of such proportions form on the side of Mount Mazama when U-shaped glacial canyons were being carved at the same time and at the same elevation a short distance away? Surely a river could not cut such a smooth-sided gorge across bedded lavas and ashes, and least of all so close to the summit of the mountain and in the short interval between successive advances of ice.

All doubt is removed by closer inspection. Then it becomes apparent that the lava occupies a funnel-shaped explosion vent and that the feeding pipe lies at the base of the great triangular cliff. Had the lava issued from a source higher up the slope of the volcano and flowed eastward down an old river gorge, the banding would dip eastward in conformity with the valley floor. In reality, the flow planes are disposed concentrically, like a series of hollow, inverted cones one within the other. Redcloud Cliff itself is not quite vertical, but inclines steeply toward the lake, and at its base there is a projecting, right-angled buttress, 20 yards long and 75 yards across, reminiscent of the larger buttress jutting from the base of Llao Rock. Within this buttress the flow planes are beautifully displayed, standing vertically and striking parallel to the margins. The conclusion cannot be avoided that this marks the actual conduit of the Redcloud dacite.

Along the borders of the great V, the lava is finely banded and locally crowded with spherulites. Partly encasing it are coarse tuff breccias consisting of angular blocks of dark, glassy dacite, up to 8 feet across, lying in an ashy matrix of the same, intermingled with white dacite pumice and occasional fragments of andesite. In places these peripheral breccias are well bedded, dipping under the lava and lakeward. Before the main flow was erupted, magma must have risen in the conduit, solidified there, and then been blown out together with pieces from the adjacent andesites. The presence of pumice among the ejecta offers a possible explanation for the explosions, suggesting that after the first surge of magma had congealed in the conduit, gases accumulated below until the pressure became adequate to blast a passage to the surface. In this way a large funnel-shaped crater was produced. Perhaps a broad and deep glacial depression already existed in the vicinity; otherwise, it is difficult to account for the paucity of old andesitic debris among the ejecta. Once the conduit had been cleared, viscous dacite rose into the crater and piled above it in the form of a low dome. Unable to move westward against the slope of Mount Mazama, the lava then began to flow sluggishly to the northeast. Despite its unusual thickness, it came to an abrupt end about a mile from the source.

We may now follow the margin of the lava northward from the vent along the caldera wall. Upward from the conduit, along the edge of the V-shaped part of the flow, several patches of coarse explosion breccia may be seen firmly adhering to the dacite within. The flow banding stands vertically, dips inward, or, in a few places, dips steeply lakeward, which, of course, it could not do if the lava had poured down a river valley in the opposite direction. Beyond the V-shaped part of the flow, the thickness of the lava diminishes to about 300 feet. Here, the banding at the bottom of the lava stands vertically and strikes parallel to the face of the cliff. In fact for a short distance the older, gently dipping andesites abut against a vertical wall of dacite. Clearly, therefore, either the dacite piled against an outward-facing cliff of andesite or some of it rose through a vertical fissure extending northward from the principal vent. Higher up, the banding of the dacite gradually flattens and dips away from the lake.

Close to the top of Skell Head, the margin of the dacite leaves the caldera rim and swings downhill for more than ½ mile. Throughout most of this stretch, it forms a line of cliffs, up to 200 feet high. Where they are highest, the cliffs are remarkably smooth and traversed by broad, almost horizontal flutings, and it comes as a surprise to find that these features are only in part the result of glacial erosion and are mainly original structures of the flow itself. Along this edge of the dacite, the lava is rich in spherulites and lithophysae lined with plates of tridymite.

Near the snout of the flow, there are several large caves, either at the base or a short distance above. One of these measures 35 feet across the mouth and 10 feet in height, and can be traced under the lava for a distance of 100 feet. It was not the escape of fluid lava from beneath a solid crust, nor was it explosion that produced these openings; they seem rather to have been caused by the rucking up of the viscous base of the lava and by shearing within the flow as layers moved differentially.

Along the southeast margin of the dacite, the banding, even at the very edge, is generally vertical and in certain places bulges outward. On the hummocky top of the flow, the planes retain steep dips and are arranged more or less concentrically. In other words, we are faced with the strange phenomenon of a thick lava flow, approximately a mile in length, in which the marginal banding rarely departs much from the vertical and the banding of the interior parts is also highly inclined over most of its surface. In view of the recentness of the eruption, the top of the flow can have been only slightly modified by erosion, and the steepness of the sides can have been increased only toward the base. If the original margins were restored, they would probably resemble those of the Watchman flow, and we should see that the banding in the lower parts lay horizontally or dipped inward at low angles, whereas in the higher parts the inward dip rapidly increased to verticality. Under the central part, the flow planes must, of course, conform with the slope of the floor, but toward the top they must curve so as to emerge at right angles to the surface. This peculiar structure has never been observed among any of the andesites of Mount Mazama except in the Watchman flow, but is typical of all the dacites. Presumably it results from shearing of layers of extremely viscous, almost solid lava over one another. In this sense the flow planes may be compared to the rising thrust planes so commonly seen in glaciers.

Although the structure of the Redcloud flow is fairly clear, that of the Cloudcap dacite is obscure. The topographic form suggests that Cloudcap itself may be a dome-shaped protrusion above a vent immediately beneath the summit. On this assumption the long flows of dacite forming Scott Bluffs may be considered as earlier products from the same source. The presumption is that the thick sheet of dacite on the caldera wall immediately below the southern extension of the Redcloud dacite is also a product of the Cloudcap vent (panorama, plate 23). At the base of this 200-foot sheet, the lava merges into 20 feet of intensely welded and banded dacite tuff rich in lithic blocks of andesite, identical with the welded tuff of the Wineglass. Beneath this lie the blocky breccias, coarse lump pumice, and tuffs that form the Cottage Rock. Clearly, the growth of the Cloudcap dome was preceded by long and violent explosions.

# The Parasitic Scoria Cones of Mount Mazama

The growth of parasitic cones and viscous domes on the flanks of a composite volcano is usually a sign of old age. Mount Mazama had probably attained its maximum elevation about the close of the Pleistocene period. Shortly thereafter, when the glaciers on its flanks had dwindled to small proportions, numerous scoria or cinder cones began to form near its base and on the surrounding flats. A few scoria cones had been formed long before, when glaciers still filled the canyons and covered the intervening divides, but by far the majority show no signs of having suffered from glaciation and their forms are consequently well preserved.

Within the limits of the park there are no less than thirteen of these parasitic cones, of which only the two small ones on the north side of Castle Creek have been modified by glacial action. Of the other eleven, three lie on or just beyond the northern slopes of Mount Mazama, namely, Red Cone, Desert Cone, and Bald Crater; one, Forgotten Crater, lies on the western slope, not far from the caldera rim; the others lie on the southern slopes or on the adjacent flanks of the Union Peak volcano.

Outside the park there are eleven other cinder cones. Though these lie beyond the base of Mount Mazama, they are of approximately the same age as the eleven cones just mentioned and were probably fed from the same magma chamber (map, plate 2).

The dacite flows of Llao Rock, Grouse Hill, Cleetwood Cove, Redcloud, and Cloudcap and the dacite domes at the eastern base of Mount Mazama also belong to this period of activity. In other words, after Mount Mazama had reached full height by the outpouring of flows of andesite, the closing stages of its history were marked by the eruption of magmas of opposite types, namely, basalt and basaltic andesite in the form of cinder or scoria cones and dacite in the form of viscous flows, pumice, and steep-sided domes. A similar sequence of events has been recognized on other Cascade volcanoes. Indeed, eruption of highly differentiated magma seems to characterize the decadence of many andesitic volcanoes the world over.

The parasitic cones now to be described show so many features in common that a brief discussion of each will suffice. All were formed primarily by eruptions of gas-rich magma as scoriaceous bombs and lapilli. A few also erupted short flows of lava.

## The Older Cones

The remains of two small cinder cones may be found on the western slopes of Mount Mazama, on the ridge overlooking Little Castle Creek. The larger of these forms the hill numbered 6236 on the geologic map (plate 3). As far as the few exposures permit judgment, the hill appears to be made up of red basaltic scoria and agglutinate. The cone, which is only about 100 feet high and less than ¼ mile across at the base, has no trace of a summit crater. A mile to the west a still smaller accumulation of red scoria probably marks the site of a second cone.

Another ruined cone is preserved on the south side of Bear Creek, 3 miles beyond the eastern boundary of the park. Here only a few crags of red scoria remain, all traces of the original form having been obliterated by the passage of ice.

Just to the east of the Dalles-California highway, near Sand Creek crossing, there is a small, oval hillock, 150 feet high, almost completely covered by granular pumice. Poor exposures of red scoria indicate that the hillock is a denuded cone now devoid of a summit crater.

## The Younger Cones

The cones to be considered next are all well preserved. For the sake of convenience the northern ones will be mentioned first, then the southern group, and lastly those outside the park.

### *Bald Crater*

This cone rises approximately 600 feet above a pedestal of glaciated, olivine-rich basaltic andesite and basalt. The greater part is composed of basaltic scoria, among which may be found occasional ribbon bombs 5 feet in length. Close to the summit there are several flows of basalt, and probably others are concealed by slides of scoria. The cone is thus composite. Mixed with the scoria are angular lithic fragments torn from the basement. The summit crater is represented only by irregular depressions, but the flanks of the cone have scarcely been modified by erosion.

### *Desert Cone*

Most of this cone consists of vesicular, red-crusted dark scoria and fine ash. Bombs up to 4 feet in length are not uncommon, and many have the spindle, almond, and spiral shapes typical of lava clots blown out in a viscous condition, the form being modified in flight. Short flows of lava oozed through the scoria near the summit, and probably others account for the spurs on the sides of the cone. The crater form has been obliterated. On the ridges extending north and south from the base of the cone there are numerous fragments of scoria, but whether these were erupted from the same source or were thrown from a throughgoing fissure is not clear.

### *Red Cone*

This is the best preserved, the largest, and probably the youngest of the three northern cones (plate 13, figure 1). Much more lava escaped from this vent than from Desert Cone or Bald Crater. Not only do flows appear on the cone, along the south rim of the crater, and on its western wall, as well as on the north and east flanks, but thick tongues of vesicular basalt make up the prominent shoulder at the southeast base of the cone. Diller held the opinion that the lavas which extend westward from the cone beyond the boundaries of the park also issued from this source, but if they did it must have been long before the cone itself was built, for the lavas are largely concealed beneath glacial drift. None can deny the possibility, however, that Red Cone was formed by revival of activity at a vent long dormant.

For the geologist anxious to collect samples of various forms of volcanic bombs, Red Cone is a happy hunting ground. Here he may find ropy, ribbon, spiral, unipolar, and bipolar bombs, some as much as 8 feet in length. With these fragments there is much agglutinate, made up of lava clots that were sufficiently sticky when they fell so that they adhered to one another, and an abundance of fine scoriaceous ash. Angular and subangular fragments of old andesite and basalt represent materials torn from the sides of the conduit at depth and perhaps also from a floor of glacial drift. The shallow crater is breached on the north side.

Though the cone itself can never have been covered by ice, the lava ridge at its south base has evidently been glaciated. Accordingly, when the cone was formed the glaciers on the north slope of Mount Mazama cannot have extended far beyond the present rim of Crater Lake. The occurrence of pumice patches on the cone shows that it was already extinct when the final eruptions of Mount Mazama took place.

### *Forgotten Crater*

In 1932, D. LeC. Evans[1] called attention to a ruined cone about ½ mile west of Hillman Peak which had not previously been described, although it is quite conspicuous from the Rim Road. It is built on a ridge of lava that descends from Hillman Peak and may lie on a radial fissure connected with that cone. This seems all the more likely since it is itself elongated in an east-west direction, measuring approximately 700 yards along its major diameter and about half as much in width (plate 13, figure 2). Along the north and west sides a continuous ridge of cinders marks the crater rim, but on the east the rim has been demolished and on the south it is almost completely buried by a flow of lava from the crater. Among the cinders are a few ropy bombs up to 2 feet in length, but small lapilli predominate. Angular lithic fragments are widespread. Especially conspicuous are the large glacial boulders on the northern rim, one of which measures 8 feet across. Whether these were blown from an underlying layer of drift or indicate that ice formerly covered the cone is difficult to say.

Within the rim of cinders lie two small craters, the eastern of which is a funnel-shaped explosion pit about 50 feet deep, probably caused by a phreatic eruption. The other crater is no more than a shallow, arcuate depression.

After the explosive activity at Forgotten Crater had come to an end, composite flows of well banded, almost pumiceous, glassy lava, crowded with crystalline inclusions, broke through the crater wall on the south side and poured a short distance beyond. A much more voluminous flow escaped from fissures at the western base of the cone and spread for a mile in that direction, ending in a series of branching tongues. Near the source this flow shows the same pronounced banding of dark, basic lava and paler, more acid material as the shorter flows on the south side of the cone, but farther away it is entirely composed of black lava. To judge by the rough, blocky surface and the steepness of the margins, this flow is probably younger than any other on the outer slope of Mount Mazama. Evans was so struck by the youthful appearance of Forgotten Crater that he ventured the opinion that it might be contemporaneous with Wizard Island and therefore be younger than the caldera itself. The presence of a light sprinkle of pumice on both the cone and the flows indicates, however, that this cannot be the case.

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[1] D. LeC. Evans, "Forgotten Crater," Nature Notes (Crater Lake National Park), vol. 5, no. 3, 1932.

### *Crater Peak*

This familiar landmark on the south slope of Mount Mazama rises 750 feet above the undulating crest of Vidae Ridge, a short distance from Tututni Pass. It rests upon and is surrounded by glacial drift. The cone itself has not been modified by glaciation and is as well preserved as any within the park. Most of it consists of lapilli and bombs of red, brown, and black porphyritic basaltic andesite like that which makes up the cone of Wizard Island. Few fragments exceed even 3 inches across, though occasional bombs about a foot in diameter are also present. Some of the ejecta are angular and have smooth, plane surfaces. Probably these were blown out when solid. Others are subrounded and scoriaceous and must have been erupted in a viscous state. With these are many lumps of old andesite and dacite torn from the underlying basement. Much brick-red ash was also blown from Crater Peak and may be seen as far as 2 miles from the cone.

The activity at Crater Peak was not wholly explosive, for several dark, scoriaceous flows of lava issued from the flanks of the cone and spread over the surrounding flats. Possibly the dark, scoriaceous lavas exposed about 2 miles southeast of the cone are also related to this vent. The summit crater is a shallow, saucer-shaped basin, approximately 150 feet deep, and is breached on its eastern side.

### *Diller Cone*

Except for the cone of Wizard Island, there is none in the park that surpasses in symmetry the one which rises from Grayback Ridge near its southern end. It is referred to here as Diller Cone, in honor of Diller's masterly pioneer work in this region. It stands more than 600 feet high on a floor of drift-covered dacite. The northern slope is blanketed with pumice, but near the top and on the eastern side there are plentiful exposures of red scoria and agglutinate accompanied by a little scoriaceous lava. Apparently the last weak explosions served to fill the crater, leaving the summit almost flat. Close to the east base there are isolated outcrops of vesicular olivine basalt, but there is no means of telling whether this lava issued from fissures at the foot of the cone or belongs to the much older, Pliocene plateau basalt series which underlies Mount Mazama.

### *Southeast Corner Cone*

Two miles from Diller Cone, in the southeast corner of the park, a small hillock of red and black scoria including a few bombs 5 feet across rests on the dacites of Grayback Ridge. No trace of a crater remains.

### *Cavern Creek Cone*

Six miles to the north is a similar craterless scoria cone, 150 feet high, bisected by the east boundary of the park.

### *The Pumice Flat Cones*

On the southeast flank of the Union Peak volcano, immediately to the east of Pumice Flat, there are three well preserved scoria cones. These, together with the Goose Nest farther south, lie on a fissure which is radial with respect to the caldera of Crater Lake. For this reason, they are regarded as parasites fed from the magma chamber of Mount Mazama.

The northernmost cone forms 6545 Hill. No lava seems to have been erupted from this vent. The explosions must have been mild, for most of the ejecta measure only a fraction of an inch to a few inches across. In the top of the cone there lies a bowl-shaped crater breached on the east.

Adjoining this cone on the south is a crescentic rim of scoria partly enclosing an arcuate ridge of lava. The eastern part of this cone has likewise been destroyed.

Farther south, forming 6627 Hill, is a third cone consisting of scoria mixed with masses of agglutinate. This cone is particularly interesting because it has a double crater. The larger and older crater is clearly of explosive origin, and it was from this that the scoria cone was mainly if not entirely built. At the north end of the flat crater floor there is a deep, rectangular pit, 100 yards long and 50 yards across, with precipitous walls. From the floor of the older crater to the bottom of the pit the drop is 90 feet; the outer wall of the pit is a cliff of lava 200 feet high. The western and eastern sides of the pit are formed by slides of scoria above and lava below. If the slides of scoria were removed, the walls of this inner pit would consist entirely of lava. Clearly this cannot have come from the pit itself. Nor can the pit have been formed by explosion; its form belies such an origin, and the absence of fragmented lava in the vicinity also rules out the possibility. The pit must therefore have been produced by collapse, probably as the result of fluxing and stoping by magma rising from below. How, then, are the lava walls to be explained? Only by assuming that they are composed of much older flows belonging to the Union Peak volcano. After the first explosions had formed the older crater and scoria cone, magma rose under the north wall, undermining it and causing it to founder. The history is analogous to that of many pit craters in Hawaii.

### *Cones outside the Park*

In the flat country to the northeast and southeast of Mount Mazama there are several scoria cones of approximately the same age as those just described. Probably they were fed from a common magma chamber. Of these the largest is Boundary Butte, a craterless cone 650 feet high, almost completely covered with pumice. Slightly more than a mile to the northeast is a second craterless cone, 350 feet high, made up of black scoria, including bombs up to 6 feet in length, agglutinate, and lava. Between these two basaltic cones lies a small dome of dacite, presumably of about the same age. A third cone of scoria, surmounted by stubby flows of olivine basalt, forms 5503 Hill, between Boundary Butte and the Dalles-California highway (figure 6). A fourth cone lies a short distance west of Sun Pass, probably on a radial fissure cutting the flanks of Mount Mazama, for the line which connects it with the southeast corner cone and Diller Cone would, if prolonged, pass approximately through the center of Crater Lake.

In the depression between the opposing slopes of Mounts Mazama and Thielsen, there are four small scoria and lava-scoria cones, of which the largest, Welsh Butte, is approximately 250 feet high.

Finally, a basaltic cone may be seen perched on a platform of dacite close to the dome of Lookout Butte. Although most of it is heavily mantled with pumice, there are many outcrops of massive and slaggy, olivine-rich basaltic lava about the summit, and fragments of red scoria are not rare on the lower slopes. The occurrence of such ejecta at this point is of especial interest inasmuch as it indicates that basalt and dacite were erupted either simultaneously or in rapid succession from vents in close proximity. It serves again to emphasize the fact that the final stages of activity at Mount Mazama were characterized by the emission of magmas of widely different composition.

# Timber Crater

In the northeast corner of the park, there is a well preserved shield volcano capped by pyroclastic cones. From the perfection of its form, this volcano may be judged at once to be among the youngest of the region. See plate 14, figure 1.

The shield is approximately 5 miles in diameter, and the volume of material erupted approximates 5 cubic miles. The shield is composed essentially of flows of olivine basalt and basaltic andesite. The only notable variation is in the texture and color of the lavas and in the degree of vesicularity. As on other shield volcanoes in the Cascades, the pale-colored lavas are less vesicular and poorer in glass than the darker lavas, and where both types occur in a single sheet, the crust is darker and contains more vesicles.

Some of the flows show surface forms suggestive of recent eruption, and several of the spurs radiating from the summit region, though covered with pumice, seem to represent flows little modified by erosion.

Capping the lava shield are the remains of two cinder cones, aligned in a north-south direction. Little is preserved of the older cone, which forms 6889 Hill, north of the summit. There is no trace of a crater. All that can be seen beneath the pumice are a few small outcrops of bright-red scoria with vesicular bombs up to 3 feet across and patches of agglutinate.

The younger cone is complex, and only slightly sculptured by erosion. It is oval in plan, and extends for a mile in a north-south direction, rising approximately 600 feet above the lava shield. Here and there small exposures of well bedded scoria may be found, though rounded bombs are extremely rare. Most of the ejecta consist of angular blocks and lapilli of dense, black vesicular basalt, presumably already solid when erupted. Accompanying the explosive eruptions were short and sluggish flows of lava.

Within the summit cone three craters may readily be distinguished. The northernmost is indicated only by a remnant of the northern rim. The other two coalesce to form a depression between 50 and 100 feet deep, measuring about ¼ mile from north to south and 250 yards across at the widest place. Probably these two vents were active at the same time, though the deeper, southern crater may have continued to erupt after the other became extinct.

We may conclude, therefore, that during the explosive eruptions which brought to an end the activity of the Timber Crater volcano, there was a southward migration of the vents, parallel to the general trend of the Cascade Range, from 6889 Hill to the present summit region, more than a mile away.

Activity at the Timber Crater volcano had certainly ended before the last pumice explosions of Mount Mazama. Its closing eruptions were probably contemporary with those which formed the parasitic cinder cones on the sides of Mount Mazama. A little gravelly drift on 6889 Hill indicates the former presence of a small icecap at that point, but the summit cone of Timber Crater and the sides of the lava shield do not appear to have been covered by glaciers. The final activity of this volcano may therefore be assigned to post-Pleistocene times.

# The Wineglass Welded Tuff and Associated Pumice

Close to the top of the caldera wall, between Pumice Point and Grotto Cove, lies a sheet of peculiar dacite tuff underlain by coarse lump pumice. Throughout most of its length of 4 miles, the tuff makes a conspicuous cliff up to 50 feet in height (plate 15, figure 1; plate 25). It forms the dark brim of the Wineglass and the brick-red layer near the top of the long slide above Grotto Cove.

From Diller's account, it is plain to see that he was much intrigued and puzzled by the singular characters of this deposit. Though he referred to it as lava, he obviously had some doubt, for he notes that "it is altogether unlike the other flows of dacite and appears to be intermediate between them and tuff." In another place he remarks that "it is decidedly like a tuff and might well be so considered were it not for the stringers of black glass intermingled with a reddish groundmass containing fragments of other material and imparting a decided fluidal structure to the mass." On the geological map, he designates it "tuffaceous dacite." When Diller wrote, the manner of deposition of such material was quite unknown, and it is not surprising that he debated whether to call it tuff or lava. Rather, he deserves credit for recognizing that it presents features of both.

Since Diller wrote, similar deposits have been found around other volcanoes, and the clue to their mode of origin has been given by Fenner's study of the tuff erupted in 1912 in the Valley of Ten Thousand Smokes, Alaska. It is now apparent that magma may be erupted and *flow* over the surface in all degrees of comminution, from the coarse, blocky state seen in many lavas to the form of ultra-pulverized dust seen in certain glowing avalanches *(nuées ardentes)*. The expansion of gases liberated from incandescent particles of magma gives to these glowing avalanches an amazing mobility by reducing internal friction, so that they flow more freely than the most liquid lava. Long after the avalanches come to rest, the constituent fragments continue to give off gas, gradually adhere to one another, and become firmly welded, while the larger lumps of viscous glass are flattened by the weight of material above. The final products are thus hardly to be distinguished from banded lava.

Diller regarded the Wineglass tuff as the latest lava on the walls of Crater Lake, for he saw that on Rugged Crest it partly overlies the Cleetwood dacite. How he reconciled this observation with his theory concerning the origin of the celebrated "backflow" in Cleetwood Cove is not clear. The present survey shows, however, that the tuff was erupted long before the summit of Mount Mazama disappeared and that in places it is capped by glacial moraines. Unfortunately, its age relative to the dacites of Grouse Hill, Redcloud, and Llao Rock remains in doubt. Presumably it is slightly younger. If so, then the Wineglass tuff was the product of the last eruption preceding the great pumice explosions which led to the destruction of Mount Mazama.

*The type section at the Wineglass.* One of the best and most easily accessible sections of the tuffaceous dacite flows and of the underlying pumice forms the brim of the Wineglass. To reach the type exposure from the Rim Road, it is necessary to descend over 50 feet of loose pumice and scoria, products of the culminating eruptions of Mazama, and then over an irregular layer of bouldery glacial debris up to 20 feet in thickness. Beneath these deposits, the flat-topped sheet of tuffaceous dacite forms a cliff between 20 and 25 feet high (plate 15, figure 1).

Most of the dacite consists of compact and finely streaked glass in shades of pink, red, orange, brown, and gray. Here and there are short, thin lenses made up of angular lithic blocks of andesite up to 2 feet across. Black strings of obsidian accentuate the banding of the varicolored matrix. Some of these measure a foot long though less than half an inch in thickness. Others are paper thin and have frayed ends. They do not seem to be any more flattened near the base of the cliff than at the top. Within 2 to 5 feet from the base, they disappear. If no more of the section were seen than that just described, one would not hesitate to classify the rock as dacitic lava. But in the lowermost part of the cliff, the massive, streaked glass passes downward, within a foot or two, into pinkish, pulverulent pumice containing many chips of andesite. Seeing only this part of the section, one would say, with no more hesitation, that the material was tuff, for essentially it is crushed and flattened granular pumice. Yet the part which seems to be tuff grades imperceptibly into that which looks like lava. Suspicion that the main body is not really lava is increased when the streaked glass is traced laterally, for on the same horizon it is possible to follow all gradations between dense, varicolored obsidian and almost incoherent lump pumice. The conclusion is then inescapable that one is dealing with a pyroclastic flow compacted and welded to various degrees owing to differences in temperature, gas content, and thickness.

This conclusion gains weight when the Wineglass deposit is compared with welded tuffs recently examined in Japan, New Zealand, and California. Around the giant calderas of Kyushu, notably around that of Aso, there are tremendous sheets of glassy ejecta almost identical with the Wineglass tuff. Mention may also be made of the welded tuffs on the "Rhyolite Plateau" of the North Island of New Zealand. Here, in Pliocene times, great volumes of fine tuff were poured from swarms of fissures and flooded an area of no less than 10,000 square miles. So closely do the tuff sheets resemble rhyolitic lavas that their origin has only lately been recognized. Marshall,[1] who discussed them in detail under the name *ignimbrites,* has shown that, characteristically, each sheet has a basal layer composed of quickly chilled and comminuted particles of glass. Above this, the tuff becomes increasingly welded, the glass shards are flattened, and the pumice lumps have collapsed. Near the top, because of the smaller load and quicker chilling, the welding gradually diminishes and the topmost layers may be as incoherent as those at the bottom. Gilbert[2] has given a splendid account of comparable welded tuffs in the Owens Valley, California.

The Wineglass welded tuff is therefore regarded as the product of glowing avalanches, erupted as an emulsion of finely divided magma spray enclosing larger incandescent clots of viscous glass in a medium of highly heated and compressed gas. The mass must have been extremely fluid, and its path was controlled by pre-existing hills and valleys. Where it came to rest in shallow depressions, as at the Wineglass, it accumulated to greater thickness than elsewhere and therefore retained its heat and gases for a longer time. Cooling slowly in these depressions, the particles of fine, plastic glass firmly adhered to one another while the larger and hotter lumps slowly collapsed and spread under the material above. On the low divides between the depressions, conditions were quite different. There the tuff was thinner, cooled more rapidly, and lost its gas earlier. For these reasons, the constituent fragments show neither welding nor flattening, but remain incoherent, and the deposits clearly betray their pyroclastic origin. In a word, the nature of the tuff is determined by the topography over which it flowed. In the valleys it resembles streaked lava; on the higher ground, it is thinner and the fragmental character is unmistakable.

Beneath the welded tuff forming the brim of the Wineglass lies a layer of loose, coarse lump pumice, the exposed thickness of which is approximately 20 feet (plate 15, figure 1). Probably similar ejecta extend downward beneath the talus for another 100 feet, to the neck of the Wineglass. The bulk of this deposit is made up of lumps of pumice between 1 inch and 2 feet across, characterized by extreme vesicularity and a shredded, silky appearance. Mixed with the pumice, and comprising about 5 per cent of the deposit, are angular lithic blocks of andesite; these were doubtless torn from the sides of the conduits as the frothy magma was expelled. In its lower part the pumice is pale cream or white, but within 3 or 4 feet of the overlying welded tuff it becomes pink or brick red. At first one is likely to attribute this discoloration to reheating by the welded tuff, since the pulverulent base of the tuff is also pink. Closer examination and comparison with other pumice deposits which can never have been reheated in this way show that this interpretation is false. Similar reddening may be seen close to the top of the latest pumice deposits filling the canyons around Crater Lake. It is apparently caused by near-surface oxidation of iron-bearing fumes escaping from the pumice as it slowly cools. This explanation is supported by the fact that within the white pumice, far below the base of the welded tuff, there are many bombs with pink or brown crusts and others which show a concentric pink layer within a millimeter or two of the surface. Tsuboi[3] has described similar pumice lumps among the products of the 1929 eruption of Komagatake and has shown that the pink color may be produced artificially when the pumice is kept at 730° C. for a period of 1 to 4 hours.

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[1] Patrick Marshall, "Acid rocks of the Taupo-Rotorua volcanic district," Trans. Roy. Soc. New Zealand, vol. 64, pp. 1–44, 1935.

[2] C. M. Gilbert, "Welded tuff in eastern California," Bull. Geol. Soc. Amer., vol. 49, pp. 1829–1862, 1938.

With regard to the Wineglass section, one more question calls for an answer. Was the welded tuff erupted immediately after the coarse lump pumice, or did a long interval of quiescence intervene? The pumice, as we have noted already, is incoherent. It would therefore have been particularly liable to erosion. Yet throughout a length of 4 miles, the contact with the welded tuff is perfectly smooth and conformable. There is no hint of any channeling. Presumably, therefore, the eruption of the welded tuff followed immediately on that of the lump pumice. Possibly the pumice was still hot and giving off gas when it was buried by the tuff, and this may explain why the pulverulent base of the latter shares the pink color of the topmost pumice.

*Sections northwest of the Wineglass.* It is instructive to make a traverse along the rim of the caldera wall in either direction from the Wineglass, if only to observe the remarkably rapid lateral variations that take place in the welded tuff. As the tuff and underlying lump pumice are traced uphill toward Roundtop, the pumice thins to approximately 50 feet and the tuff thins to about 10 feet, at the same time losing its welded character. The tuff is no longer streaked with black obsidian, but gradually merges into a yellow, orange, or brown, friable pumiceous lapilli tuff. If the tuff was once continuous over the entire top of the Roundtop lava, it has since been stripped from the higher marginal parts and is exposed only in the saddle-shaped depression over the center, where it is approximately 8 feet thick and is overlain by bouldery drift. The underlying silky lump pumice, on the other hand, can be followed uninterruptedly over the Roundtop flow, resting directly on the lava near its margins and on an intervening lens of morainic debris in the lower, central part.

In the descent from Roundtop to the shallow depression separating it from the Palisades flow, the tuffaceous dacite begins at once to thicken and become compacted again, and within a short distance it shows the same firmly welded, streaky appearance which it displays in the brim of the Wineglass. In the center of the valley it forms a 30-foot cliff underlain by some 50 feet of incoherent, white lump pumice. The two layers then continue westward over the top of the Palisades flow.

Beyond Palisade Point, on the rise toward Rugged Crest, both the pumice and the welded tuff rest on the margin of the Cleetwood dacite, but they thin rapidly and are soon lost to view. Over the center of the Cleetwood lava there is no trace of either. Near the western edge of the lava, however, they reappear and are splendidly exposed along the Rim Road. Here the tuff rests directly on the red, oxidized crust of the Cleetwood lava and consists of incoherent, pumiceous lapilli, pink and orange at the base and paling upward to yellow and buff. Were it not that elsewhere similar deposits can be traced laterally into welded tuff, the identity of the material might be doubted. A short distance to the west, the varicolored, incoherent ejecta cross the highway and descend the caldera wall, still above the Cleetwood lava, but now separated from it by the usual layer of lump pumice. Once more, as the tuff falls in elevation, it takes on a welded appearance and simulates banded lava. From the west edge of the Cleetwood flow to the east base of Pumice Point, almost a mile away, the thickness of the cliff-forming, lava-like tuff varies between 20 and 50 feet, and in many places lenticular patches of andesite blocks are embedded in its lower part. The lump pumice below thickens to 100 feet, and locally shows a distinct stratification, as shown in plate IX B of Diller's monograph. Finally, on the rise toward Pumice Point, the welded tuff thins, becomes incoherent, and disappears, though the lump pumice continues, as shown in the panorama, plate 27.

*Section south of the Wineglass.* In the opposite direction from the Wineglass, the dacite tuff may be followed for 2 miles to the top of Skell Head, where it comes to an end. The underlying lump pumice, on the other hand, continues over the summit of Redcloud Cliff. Immediately the tuff rises southward from the Wineglass, the firmly welded character and the streaky alternation of gray and black obsidian bands disappear. Once more the deposit becomes a weakly compacted mass of buff, pink, and orange pumiceous dust, lapilli, and bombs. Mixed sparingly with the pumice are fragments of andesite. Throughout most of its course the deposit varies in thickness between 4 and 6 feet, reaching a maximum of 12 feet at the head of the "Champagne Glass" slide, just before it comes to an end. Unfortunately, talus obscures the relations at the north edge of the Redcloud lava. Presumably the steep margin of the Redcloud flow prevented the tuff from spreading farther south.

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[3] Seitaro Tsuboi and Hiromichi Tsuya, "The eruption of Komagatake, Hokkaido, in 1929," Bull. Earthquake Res. Inst., vol. 8, pp. 271–273, 1930.

The extent and nature of the tuff were largely determined, as we have seen, by the pre-existing topography. But the coarse lump pumice erupted before the tuff must have been blown high above the vents and, settling from the air in showers, covered hill and valley alike. For this reason, it does not end at the margin of the Redcloud lava, but buries the top of the flow completely, and continues uninterruptedly almost as far as Kerr Notch. The relations on this rim of the caldera merit detailed description.

For a distance of 3 miles along the caldera rim, south from Skell Head, three conspicuous layers can be recognized at once (see plate 10; plate 14, figure 2; plate 23), and a fourth can be distinguished by closer inspection. These layers are as follows:

1. A topmost layer of fine pumice, scoria, and crystal ash, products of the culminating explosions of Mount Mazama, immediately before the formation of the caldera. The thickness varies between approximately 10 and 100 feet.
2. A coarse block layer, 40 feet thick on top of Sentinel Point, and between 20 and 70 feet thick above the Redcloud dacite. Though most of the blocks are angular and suggest the products of low-temperature explosions, there are many unmistakable glacial erratics, up to 8 feet in length. The balance of evidence suggests that this block layer is not of pyroclastic origin, but represents an extensive glacial moraine.
3. Below this, a third layer of coarse, silky lump pumice, usually about 40 feet in thickness and containing abundant bombs, many as much as 6 inches in diameter. Between 10 and 15 per cent of the deposit consists of angular lithic blocks of andesite, mostly less than 3 inches across, but occasionally 5 feet in maximum dimension.
4. A patchy bottom layer of bouldery glacial till resting on striated lava.

Of these four layers, the third, namely the coarse lump-pumice layer, seems to be equivalent to the lump pumice beneath the welded tuff of the Wineglass. The only notable difference is the greater proportion of large lithic blocks. This correlation is supported by the fact that on the north rim of the caldera all four layers can be distinguished, though the glacial deposits are only preserved in patches, and the welded tuff intervenes between the lower pumice and upper till.

Finally, it may be suggested that the coarse lump pumice which outcrops in Kerr Notch to a thickness of 50 feet and in Sun Notch to a thickness of 20 feet, beneath the latest glacial moraines, is also part of the same deposit that underlies the Wineglass tuff.

*Summary.* After the andesite and dacite eruptions from the Northern Arc of Vents had come to an end, glaciers readvanced down the slopes of Mount Mazama. The tops of the Watchman, Hillman Peak, Llao Rock, and the Cleetwood and Redcloud lava flows remained bare, but elsewhere the ice descended a short distance beyond the present rim of the caldera.

The ice then retreated, leaving most of the rim bare. Subsequently, powerful explosions took place and a thick stratum of coarse lump pumice containing abundant lithic blocks was deposited over most of the cone, but particularly on the north and east slopes. Immediately afterward, glowing avalanches swept down the northeast flank of the volcano. Where these came to rest in shallow valleys, they left a remarkable deposit of streaky, welded tuff; where they covered higher ground they left a weakly compacted buff, pink, and orange layer of pumiceous lapilli tuff. There is no means of determining how far these avalanches continued down the slopes, for, except at a point about a mile east of the Wineglass, their deposits are entirely concealed beyond the caldera rim by the products of later explosions.

Once more the glaciers advanced. Along what is now the north wall of Crater Lake they left patches of till on top of the welded tuff; along the east wall they deposited an almost continuous sheet of blocky detritus on top of the coarse lump pumice; in Sun and Kerr notches they covered the pumice with bouldery moraines.

A considerable interval of quiescence must have followed. Everywhere except in Sun, Kerr, and Munson valleys the glaciers withdrew above the present rim of the caldera. Within the magma chamber fundamental changes were going on preparatory to the climactic explosions which were to destroy the summit of Mount Mazama.

# The Form of Mount Mazama Just before Its Destruction

The remnant slopes of Mount Mazama show the concave profile typical of composite volcanoes, and it may be assumed with confidence that the missing slopes were steeper than those which remain. Unfortunately nothing is known of the manner in which the missing part was constructed, so that there is no means of determining just how steep they were. Nor is there any evidence to indicate the size of the former summit crater. Accordingly, estimates of the original height of the volcano can only be approximate. Nevertheless, in order to reach a conclusion as to how Crater Lake was formed, it is essential to determine as closely as possible how much of Mount Mazama has disappeared.

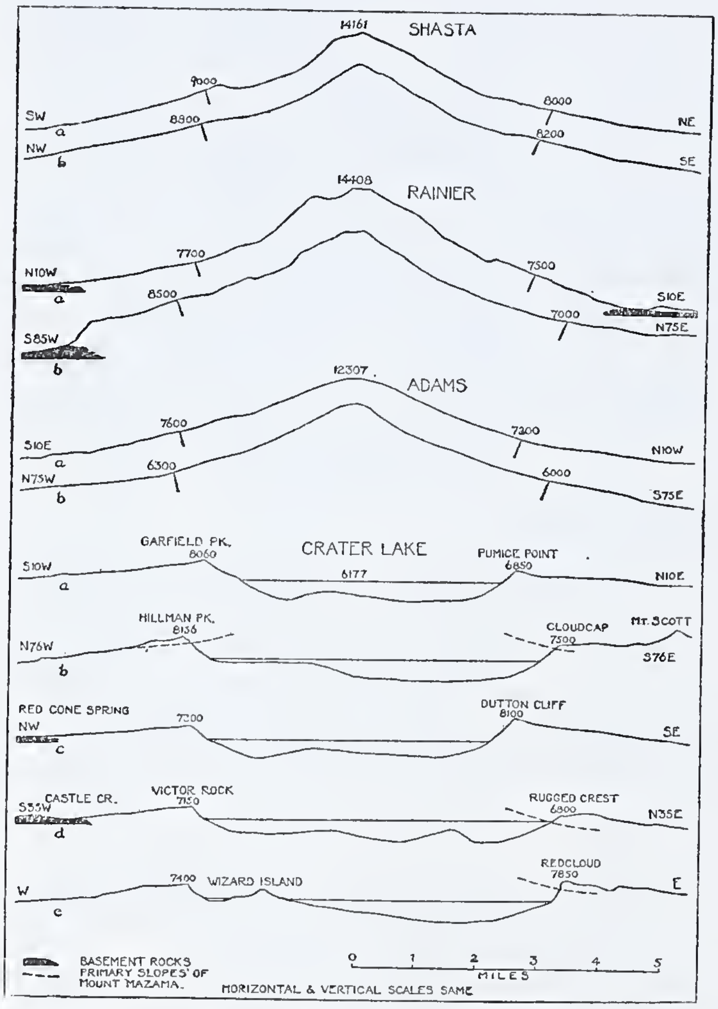

FIG. 13. Profiles through Mounts Shasta, Rainier, and Adams, and Crater Lake.

Conclusive proof of the former existence of a high cone is the fact that large glaciers, one of them at least 17 miles long, once swept down the sides of Mount Mazama. Glaciers of such size, even during the Pleistocene period, must have originated on a cone far higher than the present rim of Crater Lake. This much follows from a study of the size of Pleistocene glaciers on neighboring Cascade volcanoes.

We are aided in forming an estimate of the original size of the cone by comparing its remnant profiles with those of other Cascade volcanoes formed of similar materials, and we are assisted further by picturing the formation on these volcanoes of calderas of the same size as Crater Lake and noting the elevations of their imaginary rims (see figures 13 and 14).

Consider the rim of Crater Lake. Certain precautions must first be taken. In order to estimate the original height of the peak, the eminences on the rim which are due to parasitic, flank eruptions must be ignored and account taken only of what we have termed the "primary slopes," namely, those built by eruptions from the central, summit crater. For example, if sections be drawn across the volcano through the Watchman, Hillman Peak, Llao Rock, Rugged Crest, or Redcloud Cliff, they give a false impression, for each of these high points owes its origin to eruptions not from the summit crater, but from the flanks of Mount Mazama. That is why the profiles of Mazama seen from a distance are deceptive. They all suggest that the peak must have been higher than it probably was.

The "primary slopes" were formed by the thin-bedded andesites which make up the bulk of the caldera walls. These slopes reach their greatest elevation on the south rim of the caldera between Dutton Cliff, at a height of 8150 feet, and Garfield Peak, at 8060 feet. Along the western rim of the caldera, the

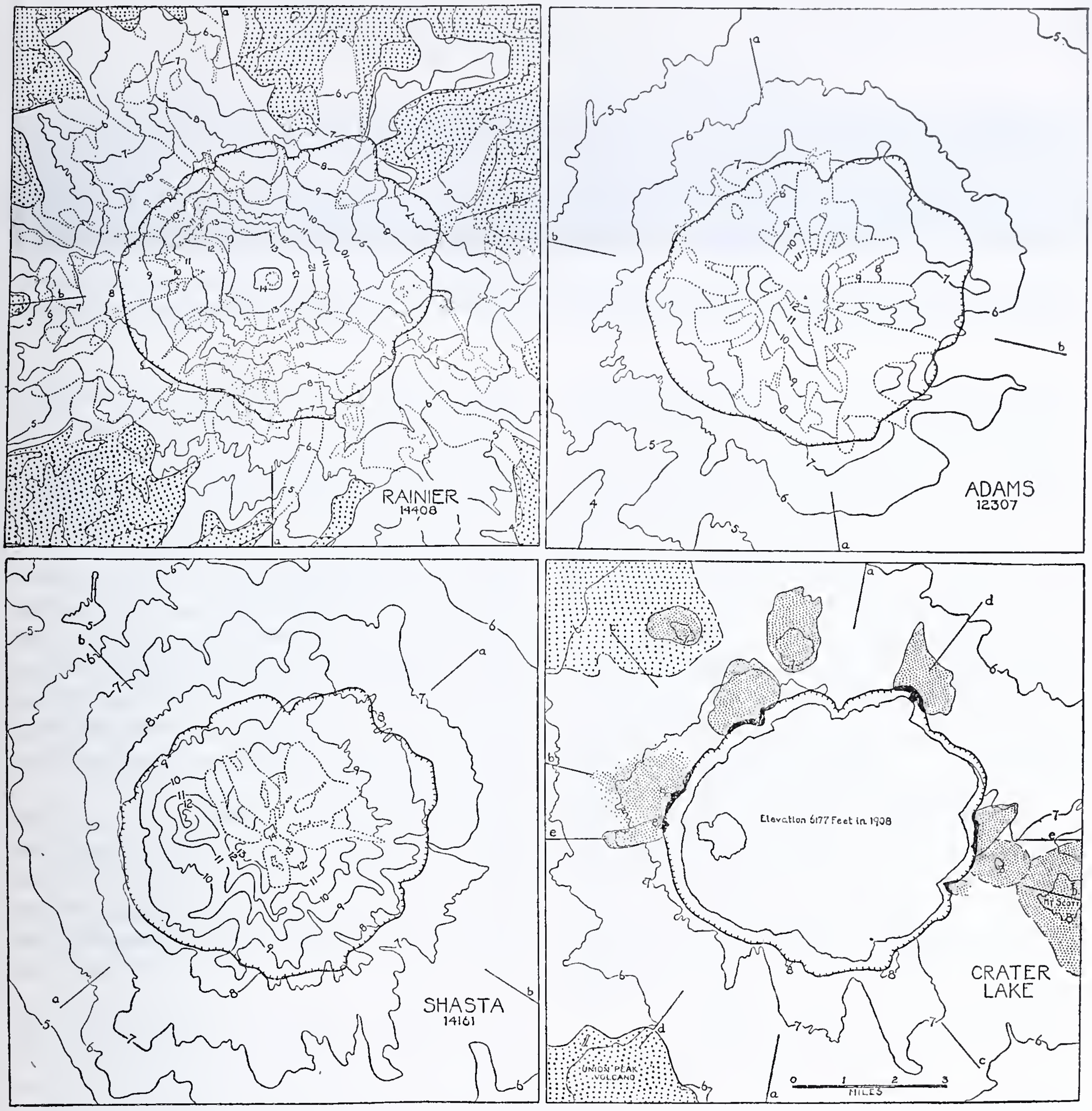

FIG. 14. The forms of Mounts Shasta, Rainier, and Adams compared with the remnant Mount Mazama. The coarsely stippled areas on the maps of Mount Rainier and Crater Lake indicate the basement rocks. The finely stippled areas on the map of Crater Lake and the black areas on the caldera wall indicate the products of parasitic eruptions. These did not increase the height of the main cone. Areas enclosed by dotted lines are glaciers. On Mounts Rainier, Adams, and Shasta, the heavy lines mark the rims of imaginary calderas equal in size to Crater Lake. The slopes outside the imaginary calderas may be compared with the remnant slopes of Mount Mazama. Section lines *aa, bb,* etc., correspond to sections in figure 13. Contour interval, 1000 feet.

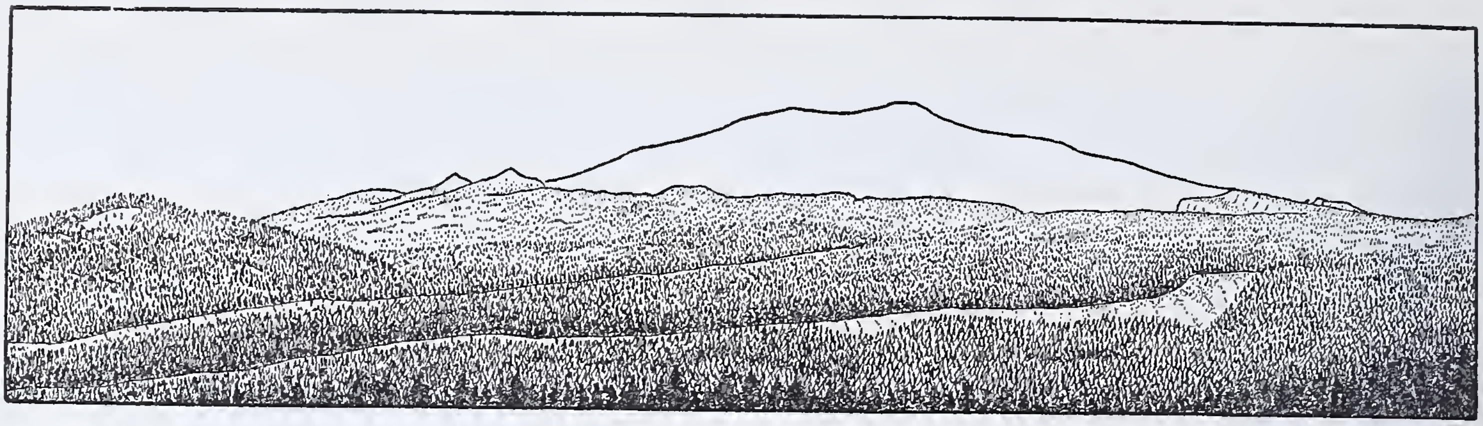

FIG. 15. Panorama of Mount Mazama from the southwest, sketched from the slope of Castle Point. In the foreground, the pumice-filled canyon of Castle Creek. The two peaks on the west (left) rim of Crater Lake are Hillman and the Watchman; the peak on the right is Garfield.

primary surface varies in height between 7000 and 7500 feet. Thence it falls eastward, passing beneath the Cleetwood flow and reaching lake level, 6177 feet, near Palisade Point. Reappearing above lake level close to the Wineglass, it rises southward to heights between 7000 and 7500 feet. In brief, the primary surface of Mount Mazama is approximately 8000 feet high on the south rim of the caldera, 6000 feet on the north, and at intermediate elevations on the other walls.

It is instructive to compare these heights with those of imaginary caldera rims on other Cascade volcanoes. For instance, if the summit of Mount Rainier were to disappear and a caldera as large as Crater Lake were to be formed, the rim would vary between 6500 and 9000 feet. More than half of the rim would lie at an elevation of about 8000 feet. Not only would most of the rim of the imaginary Rainier caldera be higher than that of Crater Lake, but the remnant slopes would be considerably steeper. Hence, if the original Mount Mazama had a crater commensurate with that of Rainier, its summit must have been at a much lower elevation, or well below 14,408 feet.

A similar conclusion is reached when comparison is made with an imaginary caldera on Mount Shasta (see figure 14).

Consider next Mount Hood, the summit of which reaches an elevation of 11,225 feet. If a caldera as large as Crater Lake were produced by the disappearance of its upper part, the rim of the depression would lie mainly between 5000 and 6000 feet, and the remnant slopes would not be unlike those of Mount Mazama. Accordingly, if the summit crater of Mazama was small it was probably higher than the top of Hood.

Several other Cascade volcanoes were examined with the same idea in mind, and the conclusion was reached that Mount Adams offers the closest comparison. Hence, Mount Mazama rose to a height of approximately 12,000 feet. The summit lay about a mile south of the center of Crater Lake.

Even if the foregoing argument be accepted, it does not follow that Mount Mazama was 12,000 feet high immediately before the formation of the caldera, for after the volcano had reached this height there may have been profound collapses on its northern side at the time of the pumice explosions from the Northern Arc of Vents. The summit may also have been lowered by glaciation.

As for the shape of the volcano, it was far from being a symmetrical cone. The thick deposits of glacial debris on the northeast wall of the caldera imply the existence of deep ice-filled cirques on that side of the cone. The great U-shaped canyons on the south side must likewise have headed back into amphitheaters.

The symmetry of the cone was also marred by parasitic cones and domes associated with the Northern Arc of Vents (see figure 15). Had the lost part of the volcano been perfectly symmetrical, the glacial scratches on the caldera rim would be directed radially. In many places, such is far from being the case. In particular, as figure 31 shows, the striae on the summit of Roundtop and near the Wineglass, instead of pointing toward the center of the caldera, converge toward a point a little to the west of Skell Head. Perhaps the semicircular form of Grotto Cove indicates the former existence of a parasitic cone in that vicinity, just as the scalloped margins of the caldera of Santorin are related to old cones that once rose above them and the semicircular Cleetwood Cove is related to the vent of the Cleetwood flow.

The glaciers which once choked the canyons and enveloped all save the topmost ridges had retreated to the upper part of the cone and were confined to the bottoms of the canyons. Only at three points did they extend beyond the present rim of the caldera, namely in Munson, Sun, and Kerr valleys on the south side of the mountain, where they lay in deep glacial troughs. A small corrie glacier may also have existed on the northwest side of Mount Scott, but the Union Peak volcano, if it was not entirely bare, supported only very small tongues of ice on the shady side of the summit pinnacle.

The slopes of Mount Mazama were almost barren of vegetation. A few tall trees grew on the moraines near the caldera rim, but thick forests were restricted to the foot of the volcano, below elevations of about 4500 feet. The sheet of pumice left by the eruptions from the Northern Arc of Vents had been almost wholly removed by erosion, leaving slopes of lava littered with moraines and fluvioglacial outwash.

# The Climax: Culminating Explosions of Pumice and Scoria

The stage was now set for the grand finale, the destruction of the top of Mount Mazama. How long a period of quiet preceded the culminating eruptions there is no accurate means of telling. But that the interval of rest was fairly long seems to be indicated by the intensity and scale of the explosions which followed. So great was the volume of material erupted, so hurriedly did it escape, and so highly was it charged with gas that the magma had probably been undergoing differentiation for a long time, building up gas pressure as it slowly crystallized. The interval of rest may have been of the order of hundreds of years. Along the north wall of the caldera, as we have seen, the welded tuff of the Wineglass is overlain by patches of glacial till, and where the tuff is absent on the east wall, a thick and extensive sheet of till rests on coarse lump pumice. Everywhere this till is succeeded by the pumiceous products of Mazama's culminating activity. Presumably, therefore, glaciers had advanced down the north and east slopes of the volcano, and had then retreated, leaving moraines in their wake, before the climactic explosions began.

Whatever the trigger action, the first explosions were not catastrophic. Like the great pumice eruptions which led to the formation of the calderas of Krakatau and Santorin, the explosions of Mazama gradually increased in violence as activity proceeded. As more magma escaped and deeper, more gas-charged layers of the reservoir were tapped, the violence of the explosions continued to grow until the chamber was largely exhausted. The history of all but a few volcanic eruptions in recent years shows this slow unfolding of energy to be a typical process. Only eruptions of phreatic type begin violently and then wane; normally, eruptions involving the discharge of new magma begin mildly and increase in intensity to the end. Certainly this is what happened at Mount Mazama. The initial explosions were weak and the pumice fragments at first were small. Later, the size and volume of the ejecta increased until toward the close the pumice was no longer shot high above the cone and dispersed by winds, but rose only a short distance above the crater and then, falling on the flanks of the volcano, rushed down the canyons in the form of glowing avalanches or *nuées ardentes*. More precisely, the early eruptions were of Vulcanian type and these increased in strength until they gave place to colossal eruptions of Pelean type.

It is impossible to remain long in the vicinity of the caldera without realizing the presence of two distinct types of pumice, radically different both in appearance and in mode of origin. One type is heavily charged with pumice lumps, some of which attain a length of more than 6 feet, set in a fine, dusty, almost flourlike matrix. This type contains many charred logs and is confined to the valleys, which it fills in places to a depth of 300 feet. The other type is much more widespread, covering hill and valley alike. In this type there is little dust and there are few lumps more than 6 inches across. Most of it consists of fragments of the size of sand or gravel, and in general it becomes finer with increasing distance from the source.

Moore,[1] who was the first to emphasize these differences, termed the coarser type *lump pumice,* and the finer *granular pumice*. Here they are spoken of as *pumice flows* and *pumice fall,* respectively, following a usage adopted by Kôzu[2] in describing similar deposits laid down during the great eruption of the Japanese volcano Komagatake, in 1929. These terms seem preferable because they stress the different modes of origin of the two types of ejecta: the pumice flows were products of glowing avalanches *(nuées ardentes)* that truly flowed down the flanks of Mount Mazama, following the dictates of topography as faithfully as any lava might; the granular pumice fell from the air in showers, and its distribution and thickness were determined largely by the vagaries of the winds at the time of eruption.

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[1] B. N. Moore, "Deposits of possible *nuée ardente* origin in the Crater Lake region, Oregon," Jour. Geol., vol. 42, pp. 358–375, 1934; "Nonmetallic mineral resources of eastern Oregon," U. S. Geol. Surv. Bull. 875, pp. 150–175, 1937.

[2] S. Kôzu, "The great activity of Komagatake in 1929," Mineral. u. petrogr. Mitteil., vol. 45, pp. 133–174, 1934.

Only close to the caldera rim is there any difficulty in distinguishing between the products of the pumice flows and pumice fall. This is to be expected, for close to the source pumice fell from the air in such large volume that it acquired little stratification and included lumps as large as those left by the glowing avalanches in the same vicinity.

Not all, but by far the greater part of the pumice which fell from the air did so before the pumice flows were erupted. Similarly, the main pumice falls at Krakatau, Santorin, and Komagatake preceded the pumice flows, and at each of these three volcanoes the flows were followed by weak, dying explosions of ash.

Having at the outset insisted on the recognition of the two principal types of pumice surrounding Crater Lake, we may now proceed to discuss each of them in detail. If the discussion seems unduly long, it may be said in explanation that the pumice deposits provide the key to the origin of Crater Lake, one of the main themes of this report, and that hitherto they have not received the attention they merit.

## THE MAIN PUMICE FALL

### *Distribution and Thickness*

The culminating activity of Mount Mazama began with the expulsion of finely divided dacite pumice, projected high above the summit of the volcano and then drifted afar and winnowed by the winds. From the distribution of this pumice (map, figure 16), it follows that during the eruptions the prevailing winds were from the same quarters as at present. At first the winds blew toward the east, but as the explosions increased in violence the winds veered toward the northeast. Two features are thus explained: first, the pronounced eastward bulge of the isopachytes toward Summer Lake and the absence in that direction of much coarse pumice, particularly in the lower part of the deposit; second, the prevalence of coarse pumice on top of the fine in the region northeast of Crater Lake.

Except near the crest of the Cascade Range, the pumice fall mantles the surface with amazing fidelity. On steep, rocky slopes much pumice has been washed to lower levels, and elsewhere it has drifted into depressions to a depth of 50 feet, but in general erosion has done little to modify the thickness of the sheet. The meager rains which fall east of the Cascade crest percolate readily through the pumice and there is little transport of material save on the banks of the principal streams. So faithfully does the pumice sheet reflect the underlying surface that test pits excavated at the tops and bottoms of large hills show the thickness to vary only within a few inches over areas of several square miles. It is as if the ejecta had been "ducoed" onto the pre-existing slopes. Where the thickness of the mantle exceeds 2 feet, hardly a single exposure of "bedrock" may be seen for miles.

The simplified isopachytes shown on the map (figure 16) are based on measurements made along highway and railroad cuts and on a large number of test pits.[3] No attempt was made to plot the outermost limit of the pumice, for where the deposit diminishes to less than 6 inches in thickness, it is generally so mixed with soil that accurate estimates are no longer possible. Nor was it feasible to plot the isopachytes within the park boundaries, for close to the source, where erosion has been more marked and where the onrush of the later pumice flows obliterated much of the pumice fall, the thickness is extremely variable. Near the northern margin of the sheet, the ejecta are buried beneath younger pumice deposits from the Newberry volcano and beneath basaltic cinders erupted from scores of cones in that vicinity. Beyond the northern limits of these younger ejecta, the pumice from Crater Lake occurs only as a light sprinkle in the soil.

A few of the outstanding features of the pumice distribution deserve to be emphasized. The margins of the deposit do not diverge from the source as might be expected, nor does the pumice thin uniformly in radial directions. On the contrary, the isopachytes run more or less parallel, and along the south and southwest edges of the deposit the pumice thins much more rapidly than elsewhere. Generally, the front of an ash or pumice fall widens with increasing distance from the vent; that it did not in this case suggests that strong winds were confined to a narrow belt. A similar lack of spreading was observed

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[3] Roy Turner's vigorous assistance in the excavations is gratefully acknowledged.

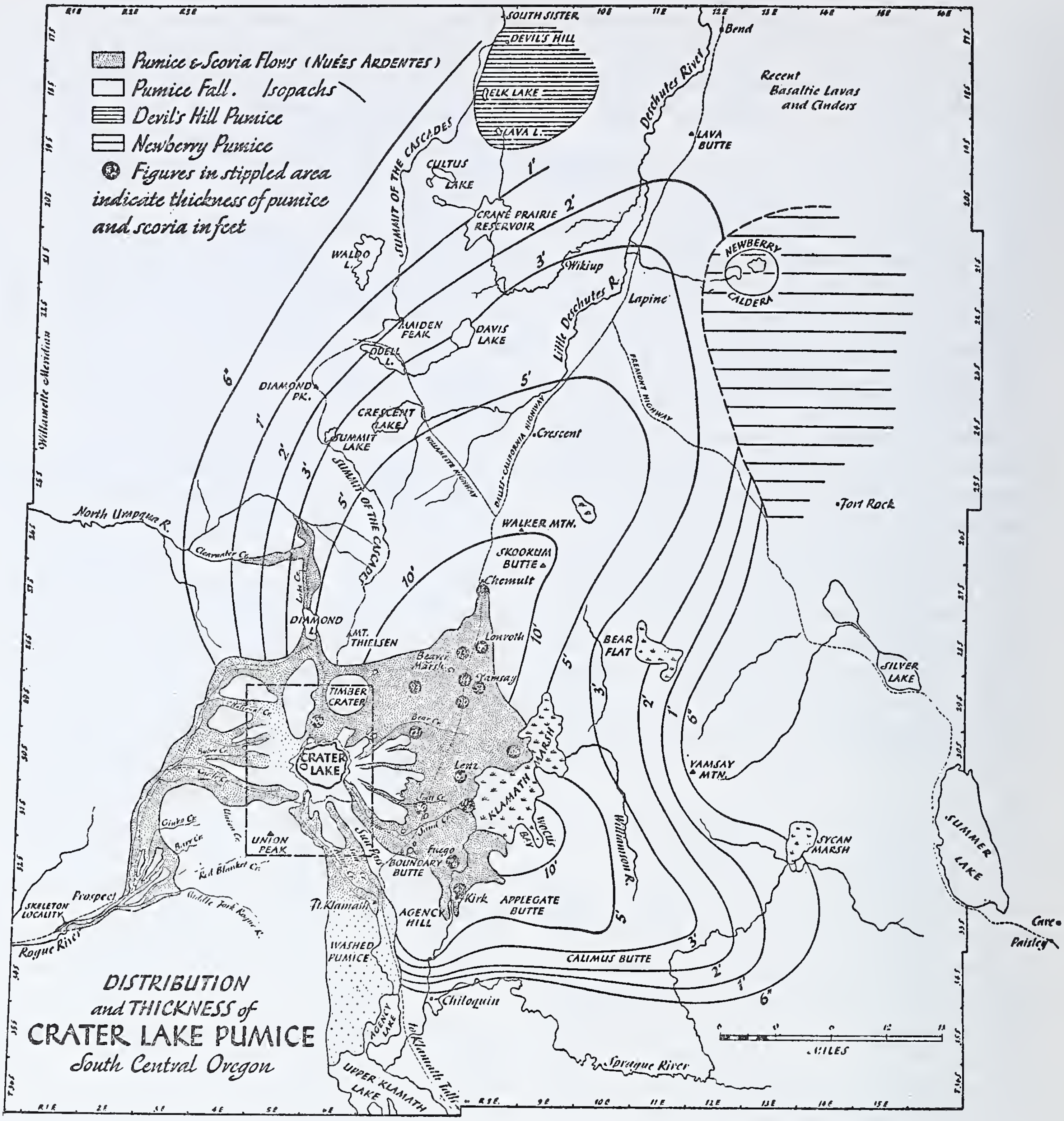

Fig. 16. Map showing distribution and thickness of Crater Lake pumice. (Drawn by A. W. Severy.)

in the pumice blown across Argentina during the 1932 eruptions of the Chilean volcano Quizapu.[4]

Even 70 miles northeast of Crater Lake the pumice sheet is still a foot thick, and it therefore goes without saying that some of the finer ejecta must have spread for hundreds of miles. Probably the finest dust, like that from the eruptions of Krakatau in 1883, encircled the globe.

Perhaps no feature of the pumice fall is more striking than the scarcity of ejecta on the west and southwest slopes of Mount Mazama, even close to the rim of Crater Lake. For example, the veneer of pumice west of the Watchman and Hillman Peak is extremely thin and patchy; on Munson Ridge it is hardly more than a light sprinkle, whereas on Vidae Ridge, a short distance to the east, the thickness locally exceeds 8 feet. Along the southwest rim of the caldera, the pumice may be absent altogether. Red and Desert cones, on the northwest slopes of Mazama, though only 2 and 4 miles, respectively, from the rim of the caldera, are so lightly veneered with pumice that it requires a careful search to find even a few fragments. Several explanations suggest themselves for the paucity of pumice so close to the source. The thinly covered slopes may have been blanketed with snow at the time of the eruptions; some of the slopes were later swept clean by the onrush of pumice flows; some may have been partly stripped by subsequent erosion. But the principal reason for the scarcity of pumice fall on the west and southwest sides of the volcano was simply that the winds were blowing in the opposite direction.

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[4] Walter Larsson, "Vulkanische Asche vom Ausbruch des chilenischen Vulkans Quizapu (1932) in Argentina gesammelt," Bull. Geol. Inst. Upsala, vol. 26, pp. 27–52, 1935.

An observer would indeed have been safe in viewing the eruptions from the slopes of Union Peak, not more than 5 miles from the rim of Crater Lake. Occasional lumps of pumice up to 2 inches across fell on Union Peak, but by far the majority were less than ½ inch across, and even these were rare. The thick accumulation of pumice on Pumice Flat, near the east base of Union Peak, cannot be a product of these final explosions from Mount Mazama, for many of the lumps measure as much as 2 feet in diameter, and their pale-gray color contrasts distinctly with the pale-buff tints of the final pumice fall. These coarser ejecta belong to an earlier explosive phase of the volcano, and are probably products of the eruptions which preceded the dacite flows from the Northern Arc of Vents. The same is true of the coarse pumice in the flats on the northwest side of Union Peak and in the depression northwest of Bald Crater.

Very little pumice fell west of Annie Creek, and scarcely a trace is to be found on the west side of the Klamath graben. On the opposite side, however, the pumice thickens with astonishing rapidity. Near Klamath Agency, for instance, the thickness increases from a few inches to more than 6 feet in a distance of only 3 miles.

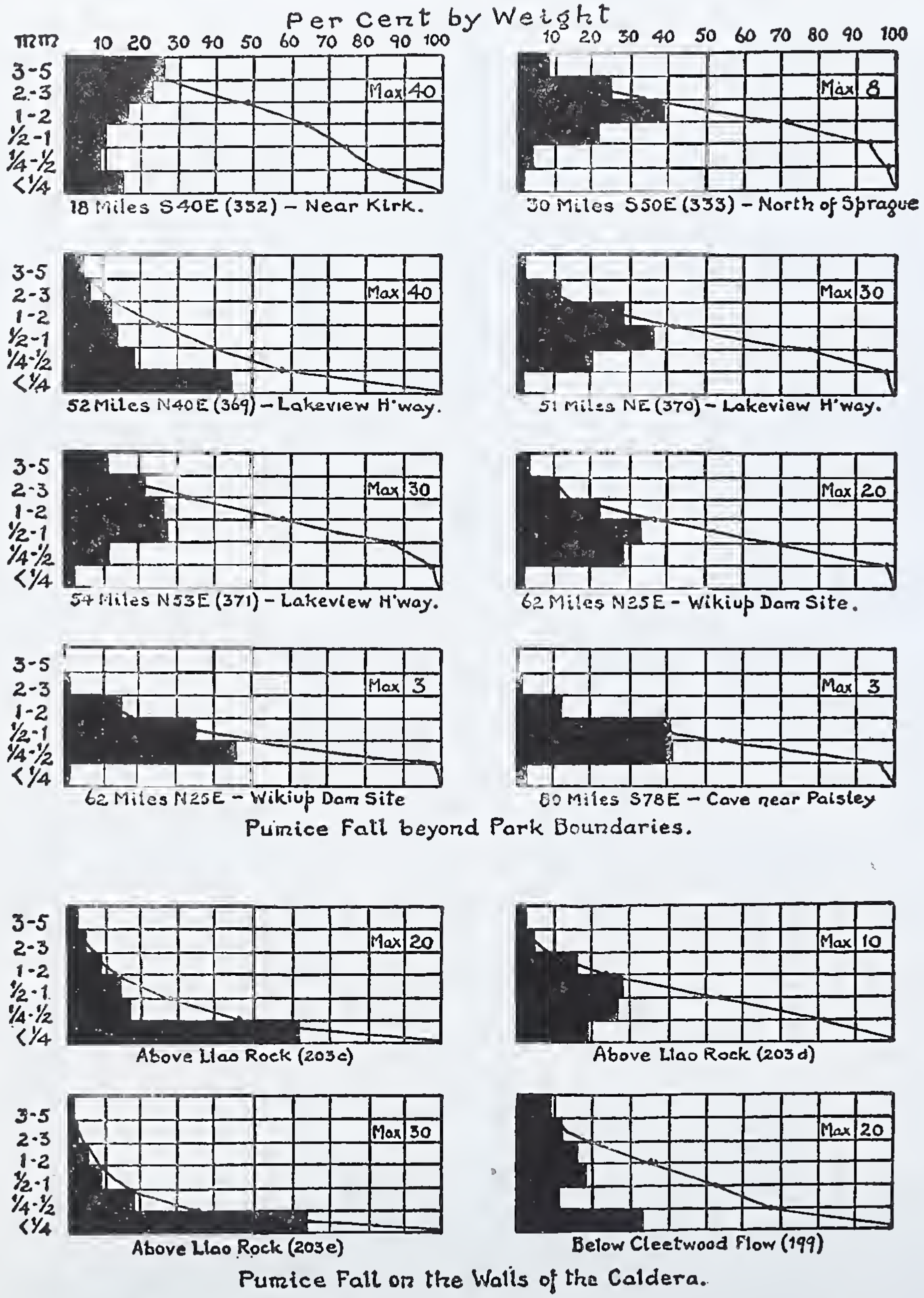
Less than 10 per cent of the total volume of pumice fell west of the summit of the Cascade Range, and much of this was swept away by the headwaters of the North and South Umpqua rivers. Thick banks of washed pumice occur far down the North Umpqua, and though most of it was derived from erosion of the later pumice flows, much of it represents products of the pumice fall washed from the neighboring hills. Certainly all the washed pumice found along the walls of the South Umpqua must be reworked pumice fall, for none of the later pumice flows entered the drainage basin of that river.

In the low country east of the Cascades, the thickness of the pumice varies gradually and regularly over long distances. Near the crest of the range, on the other hand, the variations are both rapid and irregular, and the isopachytes shown on the map are greatly generalized. To some extent, the variability in this high country is the result of erosion, but chiefly it seems to have been caused by swirling cross winds at the time of eruption. The influence of such disturbances on the thickness of ejecta was exemplified clearly during the eruption of Quizapu, already mentioned. Most of the pumice blown out during that eruption drifted eastward across Argentina, but instead of thinning regularly away from the source, the Quizapu pumice suddenly thickened in central Argentina and then continued to thin farther east. This local thickening was the result of complex eddies in the lee of the Sierra de Cordoba. We may reasonably imagine that turbulence of the winds among the peaks of the Cascades, by diminishing the transporting capacity of the air, likewise caused irregular dumping of ejecta.

Nevertheless, if these minor variations be ignored, the thickness of the pumice fall erupted from Mount Mazama varies with such regularity as to suggest that all of it was laid down within a short time. Had the eruptions continued for years, there would probably be far more irregular variation both in thickness and in distribution. Nowhere have any signs of erosion been noted within the pumice deposits themselves, nor are there any traces of interbedded soils. The probability is, therefore, that the whole eruptive episode was short-lived and that the explosions, if not actually continuous, followed each other at short intervals.

### *Lithology of the Main Pumice Fall*

Next to be considered are the variations in the coarseness of the ejecta, the proportion of crystals to



18 Miles S40E (332) – Near Kirk.

30 Miles S50E (333) – North of Sprague

52 Miles N40E (369) – Lakeview H'way.

51 Miles NE (370) – Lakeview H'way.

54 Miles N53E (371) – Lakeview H'way.

62 Miles N25E – Wikiup Dam Site.

62 Miles N25E – Wikiup Dam Site

80 Miles S78E – Cave near Paisley

Pumice Fall beyond Park Boundaries.

Above Llao Rock (203c)

Above Llao Rock (203d)

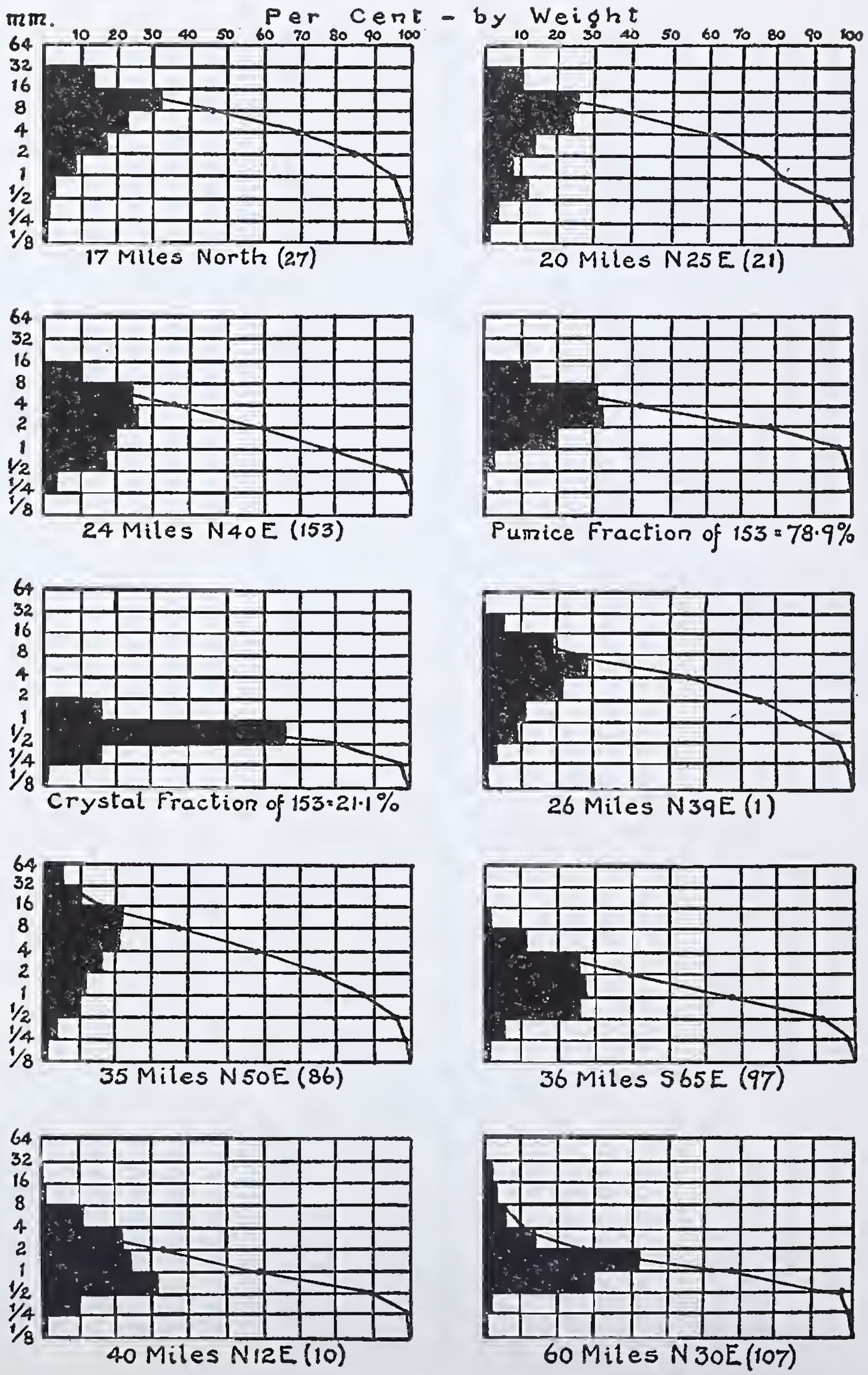
Above Llao Rock (203e)

Below Cleetwood Flow (199)

Pumice Fall on the Walls of the Caldera.

Fig. 17. Size distribution of samples of pumice fall. Distances measured from center of the caldera.

Fig. 18 (at right). Size distribution of samples of pumice fall (granular pumice). Distances measured from center of the caldera. (After B. N. Moore, *Journal of Geology*, vol. 42, p. 366, 1934. Numbers in parentheses refer to Moore's samples.)



17 Miles North (27)

20 Miles N25E (21)

24 Miles N40E (153)

Pumice Fraction of 153 = 78·9%

Crystal Fraction of 153 = 21·1%

26 Miles N39E (1)

35 Miles N50E (86)

36 Miles S65E (97)

40 Miles N12E (10)

60 Miles N30E (107)

Fig. 18

glass, and the amount of lithic detritus, that is, fragments of old lava, present among the deposits.

*Sorting of the pumice by size.* Moore[5] rendered a valuable service in preparing sixty-one mechanical analyses of samples of the pumice fall, a few of which are reproduced here as figure 18. Many more separations were made during the present study, and some are included in figures 17, 19, 20, 21, and 22.

In a general way, as might be expected, the pumice becomes finer away from Crater Lake, though the more the deposits are examined the more clearly it appears that this is indeed no more than a generalization. Commonly there is much more variation in a vertical thickness of a few feet than there is in many miles on the surface. Since, moreover, layers of a given coarseness and sorting can only be correlated over small areas, samples taken at random depths give a misleading picture. It should also be emphasized that the average coarseness does not by any means vary with the thickness of the deposits. Along the western fringe of the pumice fall, even where the thickness is less than 6 inches, lumps as much as 3 inches across are far from rare, though in other places nearer the source, where the thickness exceeds 2 feet, lumps more than an inch in diameter are exceptional.

Let it be repeated, however, that in general the pumice becomes finer with increasing distance from Crater Lake. Thus, as the histograms (figure 19) show, approximately two-thirds of the pumice that fell on Timber Crater, 8 miles from the center of the lake, consists of fragments more than 10 mm. in diameter. On the west slope of Mount Thielsen, 14 miles from the source, the percentage of such fragments is 62; near Miller Lake, on the east side of Thielsen, 21 miles from the source, the percentage drops to 25; near Windigo Pass, 25 miles from the source, it is 15; and on Skookum Butte, 30 miles away, the percentage is 18. Still farther from Crater Lake, the proportion of large lumps diminishes more rapidly. In the samples represented by figure 21, hardly any of the ejecta reach 10 mm. across.

The largest pumice lumps are to be found on Timber Crater, where many exceed 6 inches in maximum dimension, and a few reach a length of 8 inches. Lumps up to 4½ inches across may be collected as far as 30 miles from the source, on Skookum Butte and Walker Rim. Even 40 miles to the northeast there are occasional lumps 3 inches across. Seventy miles distant in the same direction, pieces between ½ and 1 inch in size are not uncommon. Clearly, most of the large lumps were drifted to the north and northeast, and were products of the later eruptions, just preceding the pumice flows. During the earlier and weaker activity, the winds blew eastward, and therefore the pumice in that direction is much finer. Even on the hills near Kirk, lumps more than 2 inches across are far from abundant. On Boundary and Lookout buttes a few pieces measure 3 inches across, but around Wocus Bay, between 20 and 32 miles from Crater Lake, the percentage of lumps more than ½ inch in diameter ranges between zero and 13 (see histograms, figure 20).

If all the pumice fragments were equally vesicular, the products of a single eruption would tend to diminish in size away from the vent. The fact is, however, that the porosity of the pumice varies considerably; some pieces are extremely cellular, whereas others are scarcely "frothed" at all. Large, light lumps may therefore be found among much smaller and more compact ejecta. Local variations in the content of large lumps must also have resulted from changes in the intensity and direction of explosions.

Generally, at any given locality the pumice becomes coarser from the bottom upward. This reflects the growing violence of the eruptions. When the explosions began to hurl out lumps between 2 and 3 inches across, the winds from the west began to veer toward the southwest. Hence in the region east and southeast of Klamath Marsh, where the deposits are more than 10 feet thick, the proportion of lumps greater than 3 inches is extremely small; farther north the proportion is high even where the deposits are only half as thick. At no time did large lumps fall south of Crater Lake. Even 2 miles south of the caldera, on the Rim Road, where the deposit is 8 feet thick, few lumps measure more than 2 inches across.

Compared with the deposits of the pumice flows, the material of the pumice fall is much better sorted (see histograms, figure 24). In view of the mode of deposition, this is not surprising, for the material of the pumice fall was subjected to long transport in the air and fell largely according to the dictates of gravity.

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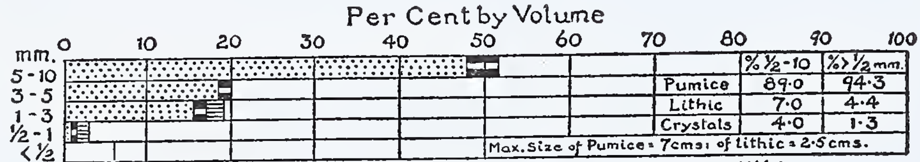
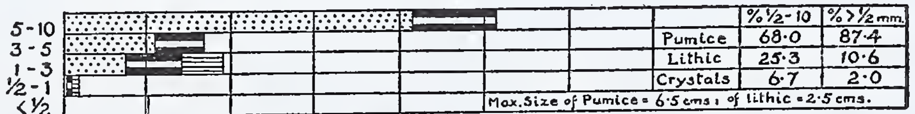
[5] B. N. Moore, *op. cit.,* 1934, 1937.



| | %½-10 | %>½mm. |
|---|---|---|
| Pumice | 89·0 | 94·3 |
| Lithic | 7·0 | 4·4 |
| Crystals | 4·0 | 1·3 |

Max. Size of Pumice = 7cms: of lithic = 2·5cms.

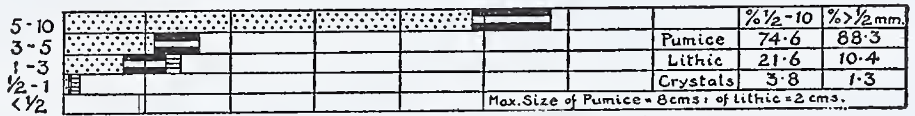
S.W. slope of Timber Crater. Depth 2 ft. %>10mm. = 62 pumice, 2 lithic.
8 miles N.18°E of center of Crater Lake.



| | %½-10 | %>½mm. |
|---|---|---|
| Pumice | 68·0 | 87·4 |
| Lithic | 25·3 | 10·6 |
| Crystals | 6·7 | 2·0 |

Max. Size of Pumice = 6·5 cms: of lithic = 2·5 cms.

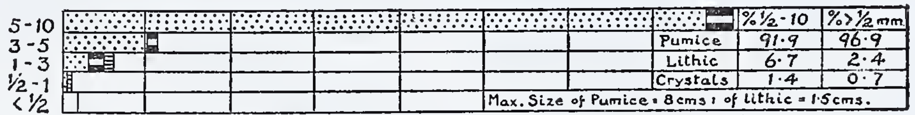
Same locality as above but depth 6ft. %>10mm. = 66·5 pumice, 3·5 lithic.



| | %½-10 | %>½mm. |
|---|---|---|
| Pumice | 74·6 | 88·3 |
| Lithic | 21·6 | 10·4 |
| Crystals | 3·8 | 1·3 |

Max. Size of Pumice = 8cms: of lithic = 2 cms.

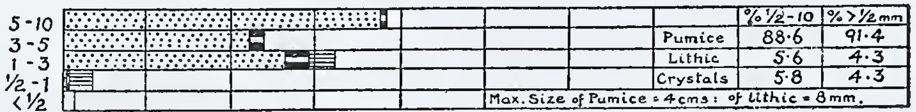
Same locality as above. %>10mm. = 61·7 pumice, 3·3 lithic.



| | %½-10 | %>½mm |
|---|---|---|
| Pumice | 91·9 | 96·9 |
| Lithic | 6·7 | 2·4 |
| Crystals | 1·4 | 0·7 |

Max. Size of Pumice = 8cms: of lithic = 1·5cms.

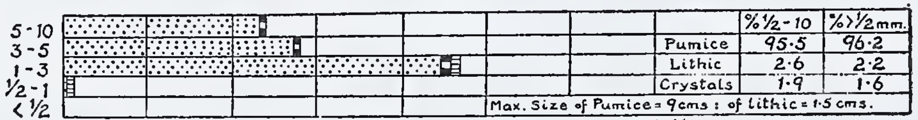
West slope of Mt. Thielsen. %>10mm. = 62 pumice. 14 miles N. of Crater Lake.



| | %½-10 | %>½mm |
|---|---|---|
| Pumice | 88·6 | 91·4 |
| Lithic | 5·6 | 4·3 |
| Crystals | 5·8 | 4·3 |

Max. Size of Pumice = 4cms: of lithic = 8mm.

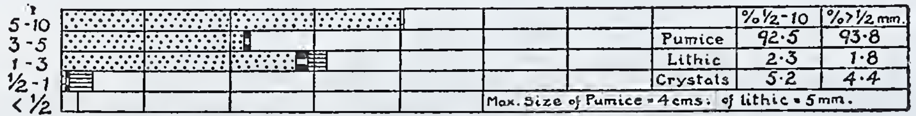
2 miles E. of Miller Lake. Depth 10ft. % > 10mm. = 25 pumice.
21 miles N27°E. of Crater Lake.



| | %½-10 | %>½mm. |
|---|---|---|
| Pumice | 95·5 | 96·2 |
| Lithic | 2·6 | 2·2 |
| Crystals | 1·9 | 1·6 |

Max. Size of Pumice = 9cms: of lithic = 1·5 cms.

5 miles S. of Windigo Pass. %>10mm. = 14·8 pumice, 0·2 lithic.
25 miles N2°E. of Crater Lake.



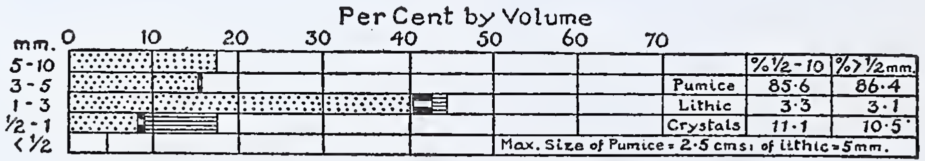
| | %½-10 | %>½mm. |
|---|---|---|
| Pumice | 92·5 | 93·8 |
| Lithic | 2·3 | 1·8 |
| Crystals | 5·2 | 4·4 |

Max. Size of Pumice = 4cms: of lithic = 5mm.

S.W. slope of Skookum Butte. %>10mm. = 18. 30 miles N46°E of Crater Lake.

▨ Pumice ▬ Lithic ▤ Crystals ☐ Undifferentiated.

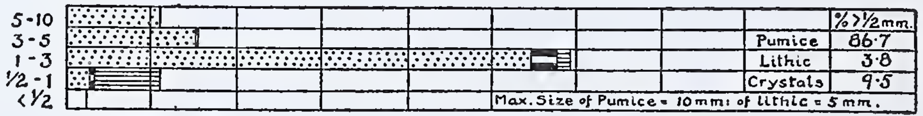
FIG. 19. Samples of pumice fall north and northeast of Crater Lake



| | %½-10 | %>½mm. |
|---|---|---|
| Pumice | 85·6 | 86·4 |
| Lithic | 3·3 | 3·1 |
| Crystals | 11·1 | 10·5 |

Max. Size of Pumice = 2·5 cms: of lithic = 5mm.

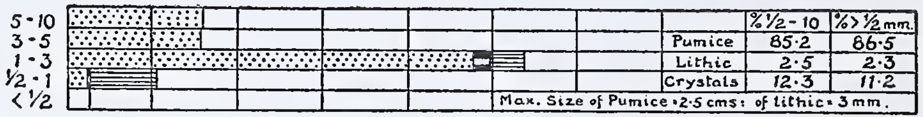
381. Between West Calimus and Yamsay Guard Stations. % > 10mm. = 4·8.
Depth = 4ft. Distance from Crater Lake = 32 miles S53°E.



| | %>½mm. |
|---|---|
| Pumice | 86·7 |
| Lithic | 3·8 |
| Crystals | 9·5 |

Max. Size of Pumice = 10mm: of lithic = 5 mm.

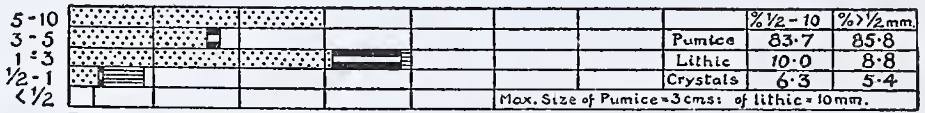
384. Between Yamsay G.S. and Wocus Bay. 32 miles S70°E of Crater Lake.



| | %½-10 | %>½mm. |
|---|---|---|
| Pumice | 85·2 | 86·5 |
| Lithic | 2·5 | 2·3 |
| Crystals | 12·3 | 11·2 |

Max. Size of Pumice = 2·5 cms: of lithic = 3 mm.

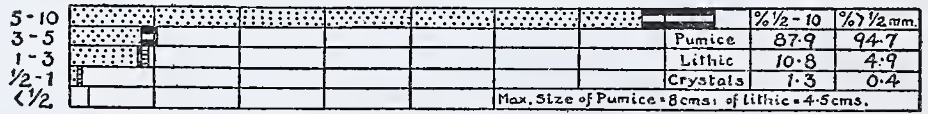
385 Head of Wocus Bay Depth 10ft. %>10mm. = 8. 25 mi. S71°E of Crater Lake.



| | %½-10 | %>½mm. |
|---|---|---|
| Pumice | 83·7 | 85·8 |
| Lithic | 10·0 | 8·8 |
| Crystals | 6·3 | 5·4 |

Max. Size of Pumice = 3cms: of lithic = 10mm.

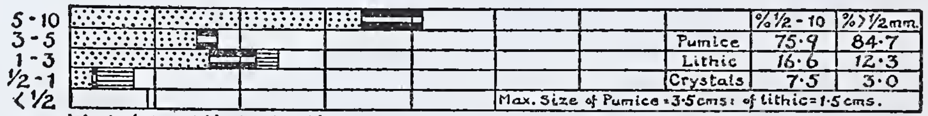
387. 2 mi. S. of Little Wocus Bay. %>10mm. = 13. 23 miles S68°E of Crater Lake.



| | %½-10 | %>½mm. |
|---|---|---|
| Pumice | 87·9 | 94·7 |
| Lithic | 10·8 | 4·9 |
| Crystals | 1·3 | 0·4 |

Max. Size of Pumice = 8cms: of lithic = 4·5cms.

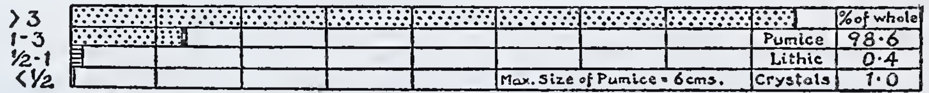
West slope of Mt. Scott. %>10mm. = 72·7 pumice, 2·3 lithic. 4 mi. E of Crater Lake.



| | %½-10 | %>½mm. |
|---|---|---|
| Pumice | 75·9 | 84·7 |
| Lithic | 16·6 | 12·3 |
| Crystals | 7·5 | 3·0 |

Max. Size of Pumice = 3·5cms: of lithic = 1·5cms.

West slope of Mt. Scott. %>10mm. = 37·5 pumice, 2·5 lithic. 4 miles E of Crater Lake.



| | %of whole |
|---|---|
| Pumice | 98·6 |
| Lithic | 0·4 |
| Crystals | 1·0 |

Max. Size of Pumice = 6cms.

386. Between Solomon Flat and Little Wocus Bay. Depth = 10ft
21 miles S67°E of Crater Lake.

▨ Pumice ▬ Lithic ▤ Crystals ☐ Undifferentiated.

FIG. 20. Samples of pumice fall east and southeast of Crater Lake

The deposits of the pumice flows, on the other hand, were laid down rapidly in the manner of avalanches and therefore suffered no sorting by wind.

Particularly striking is the paucity of fine dust in the pumice fall and its abundance in the pumice flows. Samples taken from the snout of the pumice flow which poured down the Rogue River contain no less than 70 per cent by volume of material finer than 0.5 mm. Elsewhere, more than half the flows are made up of particles less than 1 mm. in diameter. On the contrary, the proportion of fine dust is insignificant in the deposits of the pumice fall, particularly close to Crater Lake (see figure 19). Less than 1 per cent of samples taken from Timber Crater, Mount Thielsen, Miller Lake, and Windigo Pass consist of ejecta smaller than 1 mm. in size. Farther away, the content of fine particles increases rapidly (figure 21).

In the analyses listed by Moore, the contrast between the "fines" in the flows and in the fall is very clear. Considering only the fraction less than 64 mm. in size, the averages are as follows:

| | Less than 0.25 mm. (%) | 0.25–1 mm. (%) |
|---|---|---|
| Pumice flows | 36 | 27.6 |
| Pumice fall | 1 | 22 |

In other words, almost two-thirds of the pumice-flow material below 64 mm. in diameter measures less than 1 mm., though in the pumice fall less than a quarter is below that size. Furthermore, by far the bulk of the fine dust in the flows is pulverized pumiceous glass, whereas much of the dust in the fall consists of broken crystals. Many samples collected in the area south and east of Klamath Marsh contain merely a trace of material less than 1 mm. in size, and this may consist entirely of crystals. Even in the finest pumice fall examined, from the Paisley Cave, 80 miles east of Crater Lake, the percentage of dust less than 0.25 mm. in size is only 3.

The reason for the much greater content of "fines" in the pumice flows is clearly related to the comminution of the material as it was carried along in the form of avalanches, the fragments continually bombarding one another as the glowing masses swept down the sides of the volcano. Among the particles in the pumice fall there was, of course, no such mutual attrition.

*Nature of the pumice in the fall.* Close to the surface, where the pumice has been weathered, the color is pale buff or brownish, but below it is usually white or pale gray. Where vegetation is heavy, the zone of weathering may be as much as 2 feet thick, but generally it is only a few inches. Soil is either extremely thin or altogether absent.

Most of the fragments are approximately equidimensional, but many are spindle- or disk-shaped and some are drawn out into long threads. In certain fragments the vesicles are ovoid; in others they are tubular, so that the pumice has a shredded, fibrous appearance. In the larger lumps the vesicles occupy much space, but they become progressively smaller as the size of the lumps diminishes, and some of the finest dust is made up of glass shards almost wholly devoid of pores. The difference results, of course, from the bursting of gas bubbles in the larger clots. Accordingly, small shards of glass may weigh as much as cellular fragments many times larger, and for that reason ejecta of quite different sizes settled from the air simultaneously over the same regions.

Unlike the large lumps in the pumice flows, which were rounded by abrasion during transport, the larger fragments in the pumice fall are either angular or subangular. Many of the larger pieces are pink throughout; many more show a narrow pink zone a few millimeters from the surface. Apparently the pink color results from atmospheric oxidation of iron-bearing gases given off by the pumice in a heated condition. The smaller pieces fail to show the color because they were chilled too rapidly and ceased almost at once to give off gas.

Though most of the larger pumice fragments are extremely vesicular, there are a few, particularly within 20 miles of Crater Lake, which are dark gray, compact, and lithoidal. These represent clots of magma chilled quickly, probably prior to explosion.

*Crystal content.* Casual inspection gives the false impression that crystals form only a small fraction of the pumice fall. When the material is screened and examined with a hand lens, crystals are seen to be abundant. In size, they range from about 0.2 to 2 mm., by far the majority measuring between 0.5 and 1 mm. in longest dimension. In most samples, the fraction between those limits may be almost exclusively and is usually at least one-third crystals. In the larger

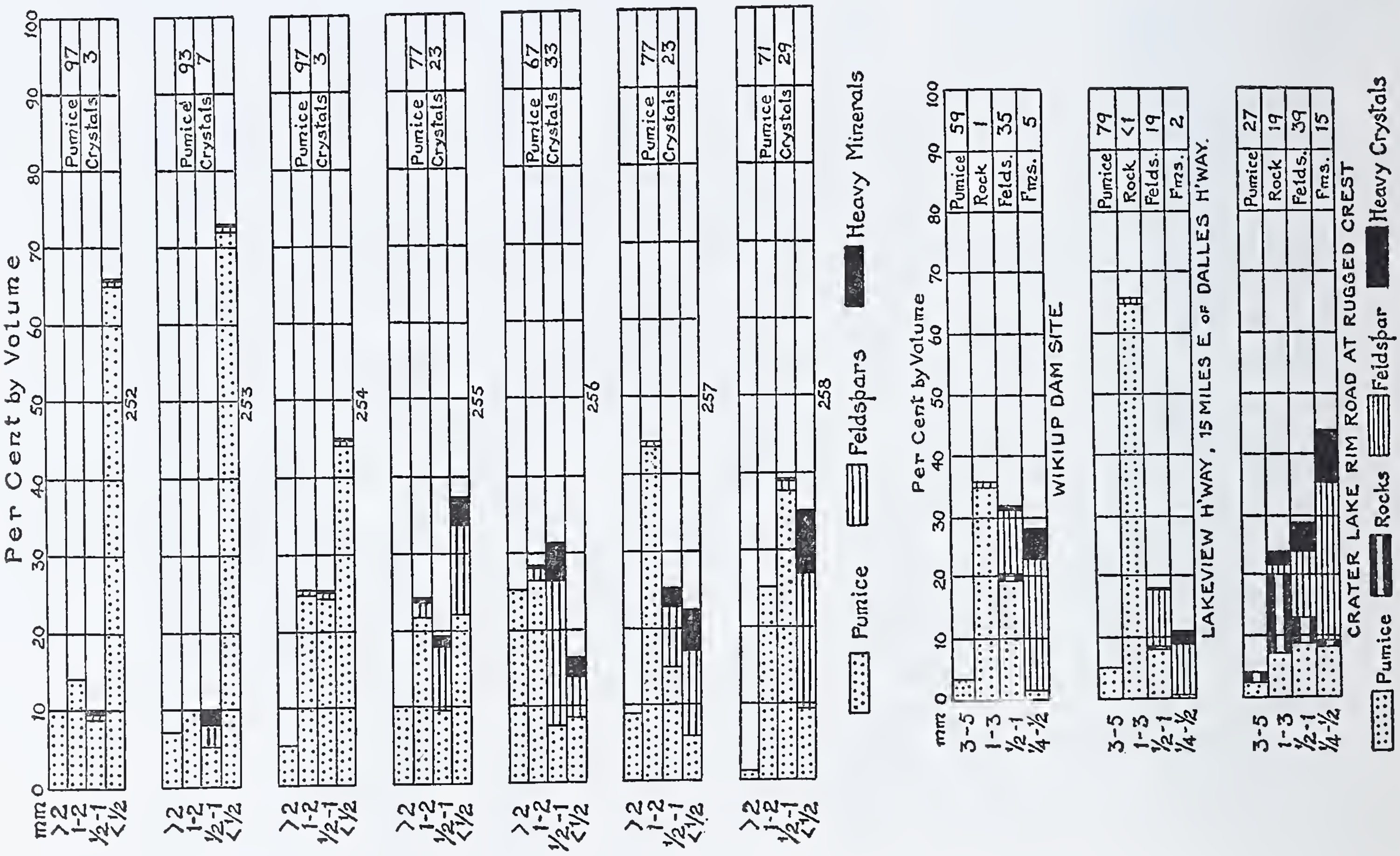


Fig. 21

Fig. 21. Samples of pumice fall. Samples numbered 252 to 258 collected on Dalles-California highway at the following distances from Crater Lake: 24, 25, 28.5, 30.5, 37, 45, and 60 miles. Wikiup sample, 60 miles NNE.; Lakeview highway sample, 48 miles NE. In samples from Dalles-California highway, content of lithic fragments omitted, but usually less than 1 per cent.

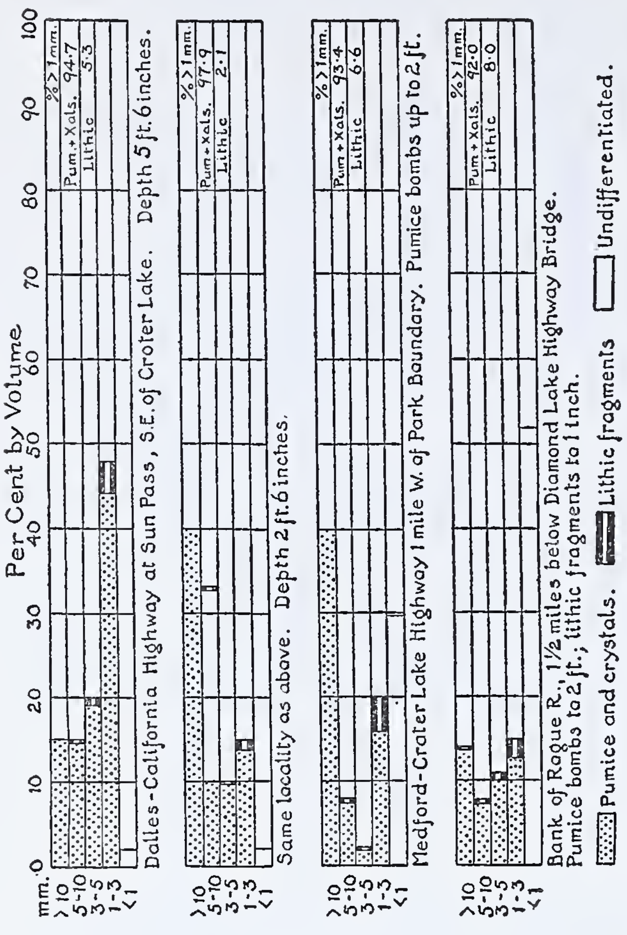


Fig. 22. Samples of pumice fall and flow. Sun Pass samples from fall; the other two from flows.

fragments of pumice many crystals are still embedded in the glass, but in pieces smaller than a few millimeters across the separation of glass from crystals is almost complete. This separation is not the result of weathering and disintegration, but an original character, caused by liberation of the crystals from the enclosing droplets of viscous glass as they spun through the air.

The ratio of crystals to glass varies between wide limits. Close to Crater Lake, where the deposits are crowded with large lumps of pumice, the volume percentage of discrete crystals commonly falls below 1. At greater distances the percentage may rise above 25, and in one sample, from Wikiup on the Deschutes River, it reaches 40. Surprising was the discovery that among the deposits bordering the Dalles-California highway, the content of crystals generally increases with the distance from Crater Lake (figure 21). In the region southeast of the Klamath Marsh, the volume percentage of crystals ranges from 1 to 11 (figure 20).

Because of the great lateral and vertical variations, and the difficulty of estimating the amount of crystals still embedded in glass, it is impossible to give an accurate figure for the total content of crystals in the pumice fall. Moore estimated the volume percentage to be about 5, but this figure seems too low. Probably 10 to 15 per cent is nearer the truth.

As to the nature of the crystals, they consist of plagioclase, hypersthene, and smaller amounts of augite and hornblende. The ratios of heavy to light minerals are shown in some of the histograms (figures 19–22). One might expect that toward the source the proportion of heavy minerals would increase at the expense of the light, but no such regular variation was observed. The only generalization which can be made is that in the marginal parts of the pumice sheet the ratio of light to heavy crystals is usually higher than it is nearer the source. In some samples feldspar may be ten times as abundant as the dark minerals, but the usual ratio is between 2 and 3 to 1. Being in general both stouter and larger, the feldspar crystals, despite their lower density, tended to fall at the same time as the heavier crystals. Changes in wind velocity, in the strength of the eruptions, and in the crystal content of the magma combine to explain the irregular variations noted above.

If our estimate of the average content of crystals, between 10 and 15 per cent, be correct, it follows that the percentage in the magma prior to explosion was much larger, for when the magma frothed into pumice its volume was greatly increased. In other words, just before the pumice eruptions the upper part of the magma chamber had crystallized to the extent of more than 30 per cent of its volume. Retrograde boiling associated with this advanced state of crystallization may well have brought about the first explosions.

*Lithic content.* In addition to pumice and crystals, the ejecta include fragments of old lava torn from the conduit walls and from the upper part of Mount Mazama. These are composed almost entirely of andesite. Bits of dacite may also be found, but ejecta torn from the pre-Mazama basement rocks are extremely rare.

Because of their greater density, the lithic fragments fell close to the source. Had the early explosions blasted away much of the upper part of the volcano, we should expect an abundance of coarse, blocky detritus near the rim of the caldera. No feature of the ejecta is more striking, however, than the paucity of large blocks of old lava close to the source. Even on Timber Crater, lithic fragments as much as 2 inches across are extremely rare and by far the bulk of such fragments measure less than ¼ inch in diameter. Still closer to the source, on the west slope of Mount Scott, few of the lithic fragments exceed 3 inches across. Most of the coarser detritus on the rim of the caldera is not of explosive, but of glacial origin.

On the sides of Mount Thielsen, lithic chips larger than ½ inch across are practically absent. Chips ½ inch across have been found as far as 30 miles from the caldera, at Windigo Pass. On Walker Rim and Skookum Butte, an equal distance northeast of the caldera, where the thickness of the pumice fall is 10 feet and many of the pumice lumps measure 4½ inches across, the largest lithic fragments are less than ¼ inch in diameter. The maximum size of the lithic fragments in other samples is shown on the histograms, figures 19–22. More than 50 miles from the caldera, chips of old lava exceeding ⅛ inch across are exceptional. The amount of lithic material that fell more than 20 miles from Crater Lake was therefore quite insignificant as compared with the bulk of the pumice and crystals.

In order to determine as far as possible the percentage of rock fragments among the total ejecta of the pumice fall, numerous screen analyses were made in the field, and a few are here recorded in histograms. On Mount Scott and Timber Crater, 4 and 8 miles respectively from the center of Crater Lake, the volume percentage of lithic fragments may reach as high as 12, or fall as low as 4. On Mount Thielsen, the percentage usually varies between 2 and 4, as it does over most of the area south and east of Klamath Marsh. North of the junction of the Willamette and Dalles-California highways, the percentage rarely exceeds 1 and is generally so small that it has been omitted from the histograms, figure 21.

Taking the pumice fall as a whole, the content of old lava fragments averages between 3 and 4 per cent, and in general it is slightly higher in the older part of the fall than in the younger. A similar paucity of lithic detritus has been observed among the pumice deposits of Krakatau, Santorin, and other calderas.[6] Clearly, the eruption of the pumice fall removed only an insignificant volume of old rock from the summit of Mount Mazama.

### *Volume of the Pumice Fall and Its Magma Equivalent*

From the isopachyte map (figure 16), it can be calculated that the volume of the pumice fall inside the 6-inch isopachyte but beyond the limits of the park and outside the boundaries of the pumice flows is approximately 3 cubic miles. To this must be added the pumice which fell within the limits of the park, where the thickness is much too variable to permit the drawing of isopachytes, and the fine ejecta which fell beyond the 6-inch isopachyte. A liberal estimate of this extra volume is 0.5 cubic mile. At first sight it may be thought that this figure is too low, since fine pumice must have covered many thousands of square miles beyond the 6-inch line. However, the volume of pumice enclosed between the 6-inch and 1-foot isopachytes, an area of more than 1000 square miles, amounts to only about 0.17 cubic mile.

Making due allowance for erosion, the total volume of pumice erupted is calculated to be approximately 3.5 cubic miles. Of this volume, between 0.35 and 0.5 cubic mile consists of crystals. The volume of old lava fragments amounts to between 0.1 and 0.14 cubic mile. Subtracting the amount of crystals and rock fragments, the volume of pumice amounts to approximately 2.8 or 3.0 cubic miles. To reduce this volume of pumice to its equivalent in liquid magma, account must be taken both of the pore spaces in the pumice itself and of the spaces between the separate pumice fragments. Making these allowances and assuming that the density of the original magma was approximately 2.3, it follows that about 1.25 cubic miles of liquid magma were erupted. Add to this the volume of crystals erupted, and the conclusion is that the total amount of material evacuated from the magma chamber was between about 1.6 and 1.75 cubic miles. It was certainly not more than 2 cubic miles.

### *Relation of the Pumice Fall to the Pumice Flows*

Moore thought that the pumice fall (granular pumice) was deposited after the pumice flows (lump pumice) because in the region south of Chemult granular pumice lies on top of the more rudely sorted deposits of the glowing clouds. He seems to have been mistaken, for the relations at Chemult are, as we shall see, abnormal. Nowhere in the area covered by the pumice flows is there a cover of pumice fall comparable with that just described. Had the main pumice fall followed the flows, the latter would be buried by a heavy sheet of granular pumice, for where the two deposits adjoin at Chemult the fall is more than 15 feet thick. Near Crater Lake, therefore, the flows would have been buried under an even thicker sheet of granular pumice. The truth is, however, that except along the margins of the pumice flow and along the axial parts of the flows in the canyons, there is no cover of pumice fall of any kind. The possibility that an overlying layer of pumice fall has been removed by erosion is out of the question.

Where the pumice flows are actually blanketed with fine pumice, the younger deposits are radically different from the main pumice fall just discussed. Notably the pumice on top of the flows in the canyons is much richer in crystals, lithic debris, and basaltic scoria; elsewhere, it is almost entirely composed of fine glass dust. Its origin is discussed on a later page, but it may be stated here that part of the ejecta represents fine dust which settled slowly from the air after the flows had come to rest, and the remainder is a product of the weak dying explosions of Mazama. The succession of events is precisely what might be expected on theoretical grounds; eruptions of pumice increase in violence until they give way to more voluminous explosions of the glowing-avalanche type, and finally the last explosions remove the debris which crumbles and slides into the conduits enlarged by the principal activity. At Komagatake in 1929 this was the sequence: first the pumice fall, then the pumice flows, and lastly the fall of dark ash.

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[6] Howel Williams, "Calderas and their origin," Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 25, pp. 239–346, 1941.

Since the main pumice fall from Mount Mazama preceded the flows, it may be asked why deposits of the fall cannot be seen beneath those of the pumice flows. The answer is that as the glowing avalanches rushed down the flanks of the volcano they plowed up and incorporated the incoherent deposits of the pumice fall. The latter, being mingled with the onrushing flows, can no longer be recognized. It must be remembered, also, that the base of the pumice flows is visible only in the canyons on the south and west sides of the volcano, precisely where the earlier fall of pumice was thinnest. The ability of glowing avalanches to scour the surfaces over which they race has often been noted by volcanologists.

## The Glowing Avalanches: Pumice and Scoria Flows

Time and again an eruptive cycle has been seen to grow from mild beginnings to a climax of great violence. As the conduits are widened and more pressure is removed above the feeding chamber, magma escapes with increasing rapidity, the more so since, coming from greater depths, it tends to have an ever increasing content of dissolved gases and so froths more and more forcibly into pumice and scoria.

The historic outbreak of Krakatau in 1883 commenced during May, and for approximately three months the intensity of the eruptions was weak or moderate. The well bedded character of the early products shows that the pumice fell from the air in showers. Late in August, activity culminated with stupendous eruptions of pumice in the form of glowing avalanches, accompanying and following which the summits of the old cones collapsed to form the present caldera. Similarly, the eruptions which led to the formation of the caldera of Santorin grew in intensity to the climax. So it was also at Komagatake in 1929.[7]

The same sequence of events took place at Mount Mazama. The earlier pumice fall was immediately followed by more powerful explosions in which the pumice escaped from the crater in too large volume and too rapidly to be thrown far into the air, but instead fell en masse on the upper slopes of the volcano, and swept downward into the canyons and thence far across the surrounding flats. Gaining momentum as they plunged down from the steep summit region, and being unusually mobile by reason of the continuous discharge of gas from the constituent fragments, they moved at prodigious speed. Each incandescent clot of magma in the avalanche gave off gas under high pressure; each time bombs burst in crashing together or against obstacles in their path, there were miniature explosions. Cushioned by highly compressed vapors, the heavy load was so mobile, and its momentum in falling was so great, that the flows rushed down the canyon of the Rogue River for 35 miles. Northward, they spread across Diamond Lake, 13 miles from the vent, and emptied into the headwaters of the North Umpqua River; southward, they poured down the canyons of Annie and Sun creeks; southeastward, they raced down Sand Creek, and even after reaching the foot of Mount Mazama continued across the flats for more than 10 miles; eastward, the flows poured out of the mouths of the canyons and spread no less than 25 miles from their source. Gravity and the auto-explosiveness of the heavy mass enabled it to travel these great distances, and it can hardly be doubted that the velocity of the flows in their upper parts was well over 100 miles an hour. Such was their power that they carried lumps of pumice 6 feet in diameter a distance of 20 miles.

In their mode of propulsion they were like the *nuées ardentes* of Mount Pelée and the "sand flow" of the Valley of Ten Thousand Smokes, Alaska. So rapidly did they rush down the steep upper slopes of Mount Mazama that they did not begin to dump their loads until they entered the canyons below or passed on to gentler gradients. Indeed, near their source they probably eroded the surface over which they moved, as the glowing avalanches of Mount

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[7] For a summary discussion of these eruptions see Howel Williams, *op. cit.,* 1941.

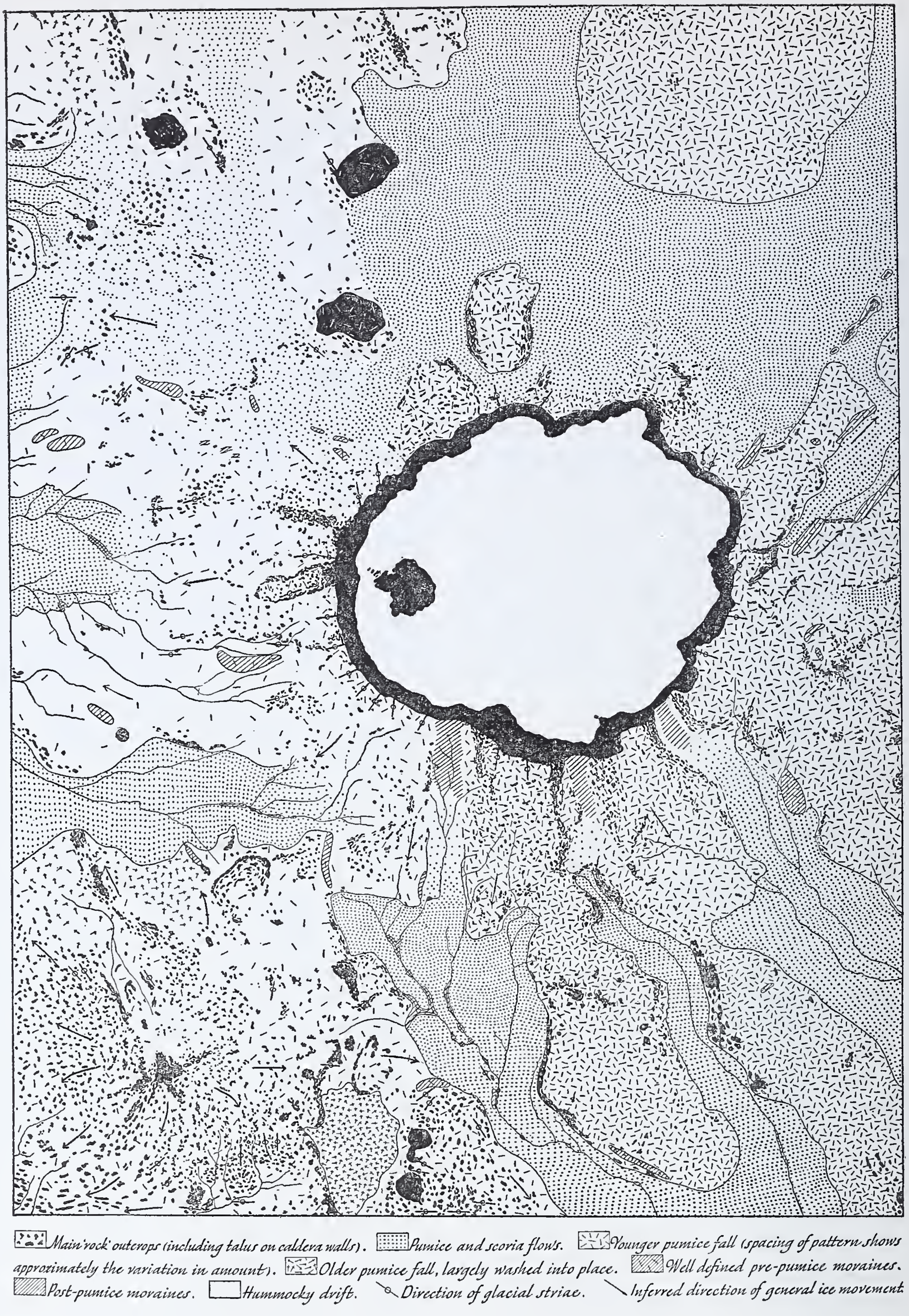

Main 'rock' outcrops (including talus on caldera walls).
Pumice and scoria flows.
Younger pumice fall (spacing of pattern shows approximately the variation in amount).
Older pumice fall, largely washed into place.
Well defined pre-pumice moraines.
Post-pumice moraines.
Hummocky drift.
Direction of glacial striae.
Inferred direction of general ice movement.

Fig. 23. Map of pumice, drift, rock outcrops, and main glacial striae

Pelée, Merapi, and Komagatake are known to have done.

Before generalizing further, it seems best to discuss the main characters of the flows.

### *Distribution*

The outstanding feature of the distribution of the pumice flows is the manner in which they follow the principal canyons around Crater Lake (see map, figure 16). Clearly the explosions were not "directed" from the summit of the volcano as downward blasts, but their course was determined largely by the topography.

On the southwest and west sides of the volcano, the flows did not begin to drop their heavy load until they had traveled about 5 or 6 miles from the source, for the slopes between the caldera rim and the headwaters of Castle, Copeland, and Bybee creeks are covered with only a thin and patchy veneer of pumice. Once the flows entered the canyons of those creeks, however, the pumice accumulated to depths of as much as 200 feet. This singular scarcity of pumice on the southwest and west flanks of the cone is only in minor part the result of erosion. The main causes were probably two: first, these bare slopes were then blanketed with snow, and, second, the flows rushed across them too swiftly to permit deposition. When their speed was checked on entering the U-shaped glacial canyons, the flows began at once to drop their detritus, and in that manner the valleys were choked and converted into the wide plains of pumice we see today.

Within the canyons, the margins of the pumice flows are usually sharp enough to be located within a few tens of yards, but where the flows were not confined by steep valley walls they spread to a feather edge, and it is difficult to see where they end against the underlying pumice fall.

The avalanches that followed the canyons of Annie and Sun creeks probably came to rest in the vicinity of Fort Klamath, having moved a distance of about 15 miles. Possibly they reached the edge of Upper Klamath Lake, which was then slightly higher than now and extended farther north. The flows that passed through Kerr Notch into the valleys of Sand and Wheeler creeks filled them to a depth of 250 feet in places. So rapidly did they move that even 13 miles from the source, after they had debouched onto the plateau at the foot of Mount Mazama, they rushed up the onset slope of Boundary Butte to a height of 200 feet.

On the east side of Mount Mazama there were no large glacial troughs; nevertheless the flows had not passed far beyond the present rim of the caldera before they were deflected into the narrow valleys of Scott and Bear creeks. These they followed down to the plateau, where they reunited and continued eastward for 10 miles or more to the edge of the Klamath Marsh. The more voluminous flows that raced down the northeast slope of the volcano along Desert Creek, combining with those which crossed the Pumice Desert and turned eastward through the depression between Timber Crater and Mount Thielsen, spread as far as Chemult, a distance of 25 miles, though the last 15 miles of their path lay across ground that was almost flat.

Part of the flow which crossed the Pumice Desert continued northward into Diamond Lake. How it crossed the lake is not clear, but that it did so is apparent, for thick deposits of unstratified pumice may be found in the upper stretches of both Clearwater and North Umpqua rivers. Another branch of the same flow swerved westward into the headwaters of the Rogue River to augment those that swept down the northwest slope of the volcano. The latter did not begin to deposit much of their load until they reached the head of National Creek, between 8 and 9 miles from the vent.

Much of the pumice which poured down National, Bybee, Copeland, Castle, and Union creeks united to form a single flow in the valley of the Rogue, and the composite mass rushed another 20 miles almost to the site of the present village of McLeod.

As compared with the deposits left by glowing avalanches around other volcanoes, those of Mount Mazama are unusually large. Even in a straight line, the snout of the Rogue River flow is 35 miles distant from the source; the actual distance traveled must have been more than 40 miles. By contrast, the great "sand flow" in the Valley of Ten Thousand Smokes was 11.5 miles long, and few of the pumice flows and glowing avalanches of Pelée and Komagatake spread more than 4 miles from their source. The Crater Lake deposits compare, rather, with the widespread tuff sheets which encircle the caldera of Aso, Japan, or

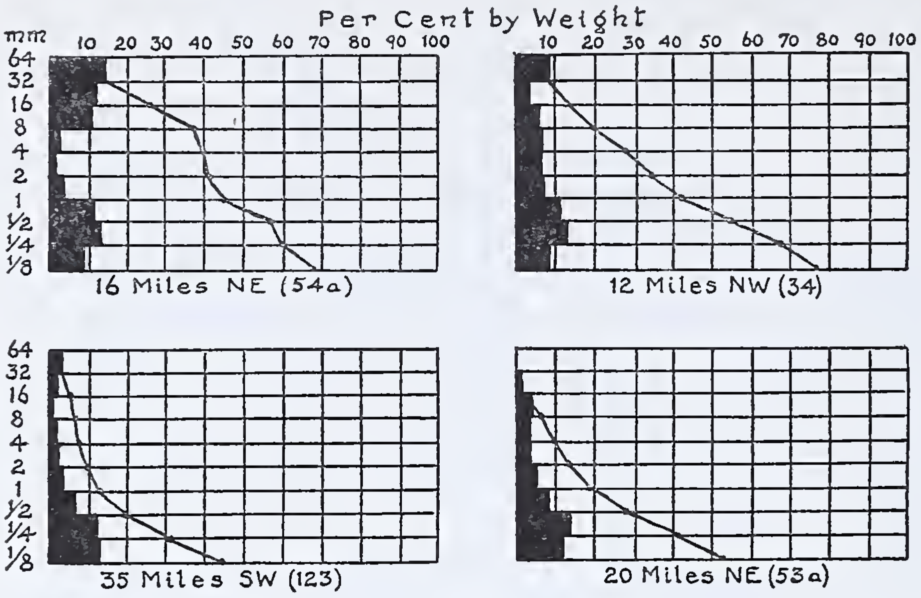


FIG. 24. Size distribution of samples of pumice flow (lump pumice). Fraction less than ⅛ mm. omitted. (After B. N. Moore, *Journal of Geology*, vol. 42, p. 365, 1934. Numbers in parentheses refer to Moore's samples.)

with those that form the extensive plateaus around the collapse depressions of Lakes Ranau and Toba in Sumatra and Lake Taupo in New Zealand.

### *The Lack of Sorting*

From what has been said it may be anticipated that the deposits of the glowing avalanches show a chaotic mixture of ill assorted fragments. Such is strikingly the case. Essentially, the deposits consist of large, subrounded pumice lumps in a dusty matrix. Nor is there any regular variation in coarseness as the flows are followed away from their source. In fact, the size of the pumice lumps bears no relation to distance from the vent, and the largest, up to 14 feet in diameter, occur 20 miles away. Lumps more than 1 foot across are plentiful throughout, and in general they are somewhat more rounded at the distal ends of the flows, owing, no doubt, to longer abrasion.

In the description of the earlier pumice fall, stress was laid on the scarcity of material less than 1 mm. in diameter, and the still more pronounced scarcity of material less than 0.5 mm. across. But in the pumice flows, the proportion of fine dust is extremely high. For emphasis it may be repeated that in the fraction of the flows less than 64 mm. in diameter approximately two-thirds consists of particles less than 1 mm., and even the portion less than 0.25 mm. in diameter averages 36 per cent. Whereas the weight percentage of material between 0.125 and 0.25 mm. in the pumice fall averages only 0.9 per cent, that in the flows averages 11.7 per cent.

Considering the manner in which the material of the flows was transported, this extraordinary abundance of fine dust is not to be wondered at, for not only were the larger lumps of pumice rapidly triturated and abraded by crashing against one another, but they must have been repeatedly shattered by internal explosions.

Typical histograms of the pumice flows are shown in figure 24, reproduced from Moore's paper. From these it may be seen that the deposits show far less sorting by size than do those of the earlier pumice fall. Chaotic mixture of fragments of all sizes is typical of glowing-avalanche debris; so is the absence of any regular, lateral variation. For these characters, rapid deposition and the absence of wind action during transit are largely responsible.

### *The Paucity of Stratification*

Being deposited in avalanche fashion, the pumice flows usually show no trace of stratification and at best a crude one. Here and there thin lenses and stringers of fine tuff among the coarser materials suggest the settling of swirls of dust during lulls in the passage of successive flows. Locally, also, there is a rough alignment of the large lumps near the base of the flows, probably caused by deformation under load. Apparently, however, the pumice lumps were neither hot enough nor sufficiently rich in gas to suffer welding. Bedding is most conspicuous in the canyons of Annie, Sun, and Sand creeks, where the earlier deposits of pale dacite pumice are overlain by a darker layer of basic scoria. Within individual flows there is usually no stratification whatever. See, for example, plate 15, figure 2.

### *Abundance of Charred Logs*

Most of the pumice fall, certainly most of that which fell beyond the base of Mount Mazama, was too cool when it came to earth to set fire to the vegetation. Accordingly there is little charred wood in the deposits except close to the caldera. In the pumice flows, on the other hand, charred logs are abundant, for the temperature of the material was much higher, and the ejecta, not being projected into the air, cooled slowly. Trees entombed in the pumice were gradually carbonized. Even at the snout of the Rogue River flow, charred logs up to 3 feet in diameter are quite common.

Small twigs and branches of charcoal do occur at the base of the flows in the canyons on the south side of Crater Lake, but they are rare. Indeed, nowhere within the limits of the park is charred wood common. But beyond, particularly along the Rogue River and wherever deep excavations have been made in the flats along the Dalles-California highway, charcoal logs may be collected in large numbers (plate 15, figure 3). When the eruptions took place the upper slopes of Mount Mazama must therefore have been almost free of vegetation. Trees were only plentiful below about 4500 feet, and even there they cannot have been as closely spaced as they are today. Had the forests been as thick as they are now, the flows could not have spread as far as they did, for their energy would have been quickly dissipated.

### *Double Character of the Deposits*

Probably more than seven-eighths of the flows consists of pale-gray and buff dacite pumice similar mineralogically to the material of the preceding pumice fall. The pumice itself is highly vesicular and often fibrous, and lightly charged with crystals of plagioclase, pyroxene, and hornblende. In the fraction less than 1 mm. in diameter, the content of crystals ranges from a quarter to two-thirds and averages about a third, feldspar predominating over the heavier minerals. The ratios of the minerals and their amounts in typical samples are shown in figures 22, 25, and 26. After the magma chamber had been exhausted of its dacitic part, the pumice flows were immediately followed by avalanches of smoke-gray basic scoria. These dark scoria flows are well seen in the canyons of Annie, Sun, Sand, and Castle creeks, where they make a striking contrast with the underlying pumice (plate 16). The transition between the two deposits takes place within a few feet. There are no intermediate andesitic ejecta. Elsewhere it has been shown that the building of the main andesite cones of Mounts Mazama and Shasta was followed by extrusion of thick masses of dacite and formation of basaltic cinder cones. The culminating pumice and scoria eruptions of Mazama likewise involved the expulsion of the two extreme magma types in rapid succession.

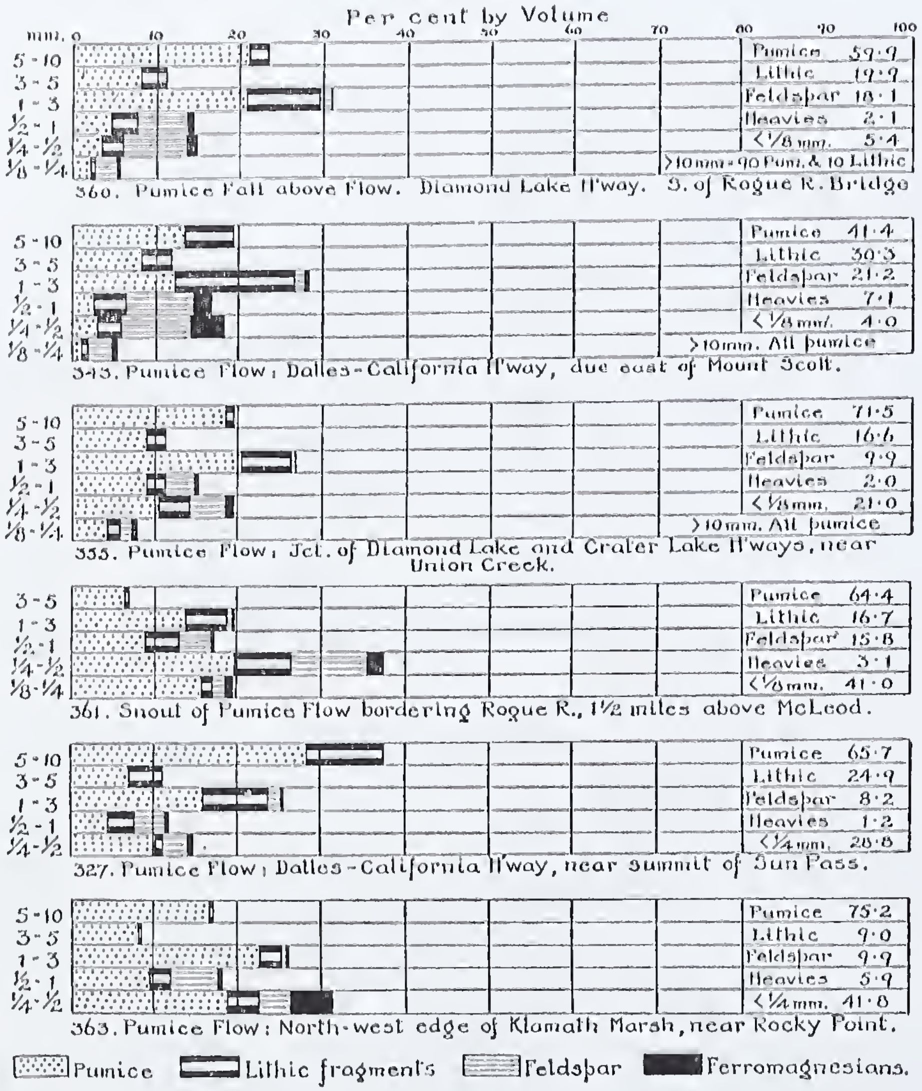
The basic scoria flows did not spread so far as the earlier pumice flows; many of them extended no farther than the limits of the park. Where they followed the canyons they were restricted to the central parts, as if they poured down median depressions in the pumice deposits and to some extent carved their own channels. On the north and northeast sides of the volcano they spread more widely, covering much of the so-called Pumice Desert and flooding the wide valley of Desert Creek. Some of the basic ejecta even traveled as far as the eastern foot of Mount Mazama and well out toward the Klamath Marsh.

In the canyons, the dark scoria commonly shows a well developed columnar structure (plate 17, figure 1), caused by slow cooling of the compacted ejecta. So well is this structure developed that the deposits have often been mistaken at a distance for columnar flows of basaltic lava.

Most of the basic scoria consists of highly vesicular brown glass, heavily charged with slender prisms of hornblende and fewer crystals of pyroxene and plagioclase. Some bombs, particularly in the Pumice Desert, are almost wholly composed of hornblende prisms.

Compared with the pumice flows immediately below, the scoria flows are generally much more crystalline. A few typical samples will illustrate the point. Considering only the fraction in the size range 0.25 to 10 mm., the pumice flow in Godfrey's Glen carries only 3 per cent by volume of crystals, whereas the overlying zone, transitional between the pumice and scoria flows, carries 9.6 per cent and the dark scoria, 10.4 per cent. Farther down Annie Creek, at the main falls, the pumice flow contains 8.7 per cent of discrete crystals and the scoria above carries 14 per cent. There are, however, other pumice flows which are richer than any of the scoria flows in crystals, as the histograms, figures 25 and 26, show.

Another feature distinguishes the pumice flows from the scoria flows, namely, the higher proportion of heavy minerals in the latter. Though the ratio of feldspar to heavy minerals in the pumice deposits ranges between 5:3 and 7:1, averaging approximately 3:1, the ratio in the scoria flows rarely departs much from



360. Pumice Fall above Flow. Diamond Lake H'way. S. of Rogue R. Bridge

343. Pumice Flow; Dalles-California H'way, due east of Mount Scott.

335. Pumice Flow; Jct. of Diamond Lake and Crater Lake H'ways, near Union Creek.

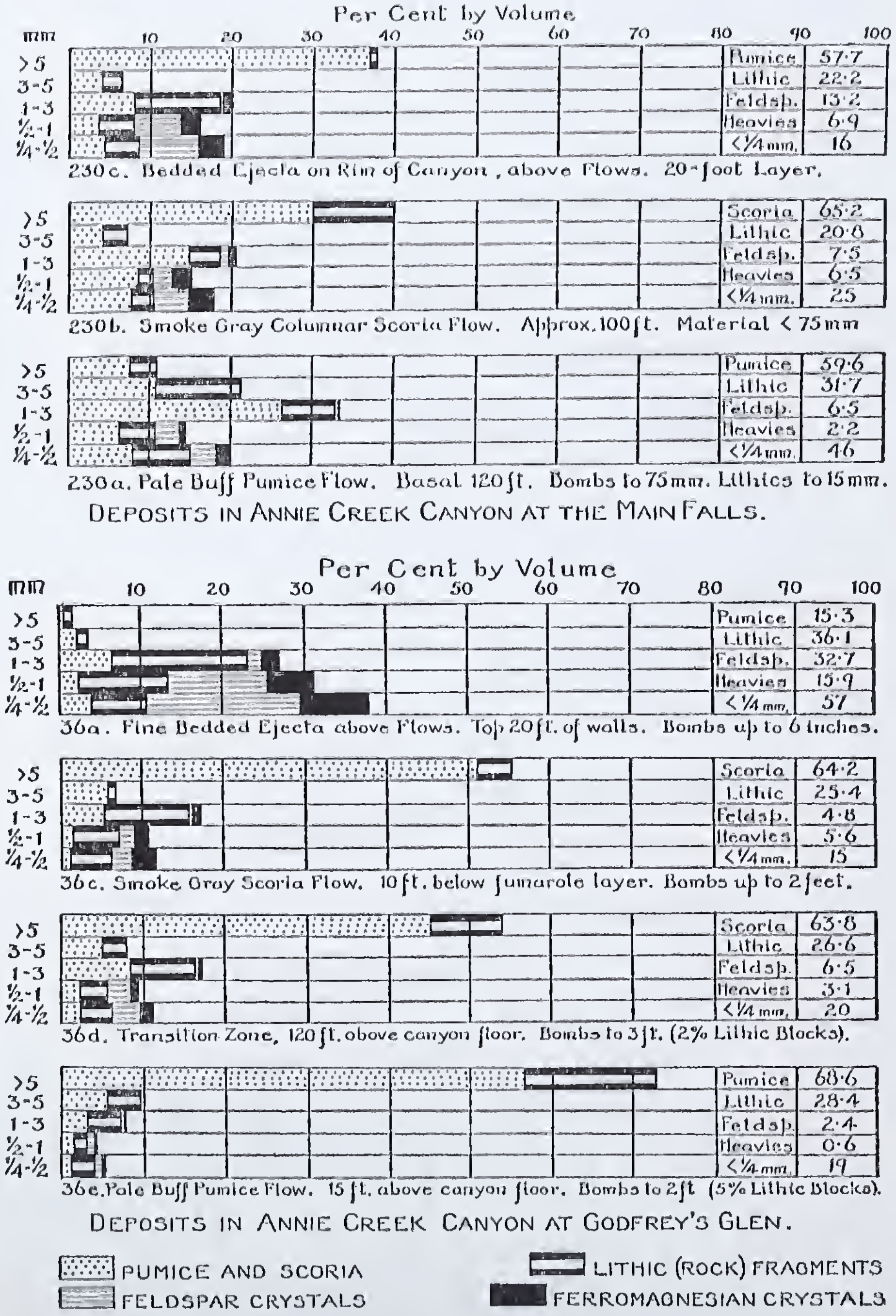
361. Snout of Pumice Flow bordering Rogue R., 1½ miles above McLeod.

327. Pumice Flow; Dalles-California H'way, near summit of Sun Pass.

363. Pumice Flow: North-west edge of Klamath Marsh, near Rocky Point.

▨ Pumice ▭ Lithic fragments ▤ Feldspar ■ Ferromagnesians.

Fig. 25. Histograms of pumice deposits. All but the first from pumice flows.



230c. Bedded Ejecta on Rim of Canyon, above Flows. 20-foot Layer.

230b. Smoke Gray Columnar Scoria Flow. Approx. 100 ft. Material < 75 mm

230a. Pale Buff Pumice Flow. Basal 120 ft. Bombs to 75 mm. Lithics to 15 mm.

DEPOSITS IN ANNIE CREEK CANYON AT THE MAIN FALLS.

36a. Fine Bedded Ejecta above Flows. Top 20 ft. of walls. Bombs up to 6 inches.

36c. Smoke Gray Scoria Flow. 10 ft. below fumarole layer. Bombs up to 2 feet.

36d. Transition Zone, 120 ft. above canyon floor. Bombs to 3 ft. (2% Lithic Blocks).

36e. Pale Buff Pumice Flow. 15 ft. above canyon floor. Bombs to 2 ft (5% Lithic Blocks).

DEPOSITS IN ANNIE CREEK CANYON AT GODFREY'S GLEN.

▨ PUMICE AND SCORIA ▭ LITHIC (ROCK) FRAGMENTS
▤ FELDSPAR CRYSTALS ■ FERROMAGNESIAN CRYSTALS

Fig. 26. Histograms of pumice-scoria flows in Annie Creek canyon

1:1. Presumably this increase in heavy minerals among the scoria flows was caused by gravitative settling in the magma chamber prior to eruption. For the same reason, the final ash fall which followed the scoria flows is abnormally rich in crystals.

Significant in connection with the mode of deposition of both the pumice and the scoria flows is their high porosity. Coupled with the high content of fine dust, it signifies continuous frothing of the ejecta during transport. It was this auto-explosive property that enabled the flows to move for such long distances even down slight gradients.

Neither the pumice flows nor the scoria flows contain more than a very few breadcrust bombs. The reason is not far to seek: in order to form breadcrust surfaces, bombs must be suddenly chilled on the outside while the gases within continue to expand and produce tension cracks in the glassy skins. When bombs are blown high in the air the tendency is, of course, for the crust to chill to glass. If, on the other hand, the bombs remain hot until most of their gas is exhausted, as they must do in glowing avalanches, they fail to acquire glassy "breadcrusts." Accordingly the conclusion seems warranted that when the pumice and scoria flows were erupted, few of the ejecta rose high above the crater. The bulk of the fragments fell to earth almost at once and, enclosed in the hot gases of the avalanches, lost their heat slowly.

### *Content of Lithic Fragments*

Moore expressed the opinion that there is a lack of "accidental" or foreign material in the pumice and scoria flows; on the contrary, we have found that they may be readily distinguished from the preceding pumice fall by their richness in such debris. In the main pumice fall, as we have seen, it is rare to find old lava fragments more than 5 cm. in diameter, and the total content of lithic debris averages only between 3 and 4 per cent. In the flows, on the other hand, the percentage of lithic material in the size range between 0.125 and 10 mm. varies between 9 and 31.7 and averages approximately 25 (figures 25, 26). The amount of lithic material less than 1 mm. in diameter is laborious to estimate, requiring careful bromoform separation. No attempt was therefore made in the field to calculate this fraction. The coarser ejecta were readily screened and separated by flotation in water. It was then found that, considering all material larger than 1 mm. in diameter, the percentage of lithic detritus in the combined pumice and scoria flows averages approximately 15 to 20, being higher in the scoria than in the pumice. These figures, it will be seen, are smaller than those given for the lithic content in the size range 0.125 to 10 mm. The reason is that there are few old lava fragments larger than 3 inches in size, whereas bombs of pumice occasionally reach a diameter of more than 6 feet, and bombs of scoria 3 feet across are not uncommon.

It might be supposed that the rapid eruption of many cubic miles of magma would be attended by the expulsion of large blocks of lava torn from the sides of the conduit and the summit of the volcano. Yet such blocks are rare. The debris torn from the sides and top of Mount Mazama during the eruption of the glowing avalanches is mostly of the size of coarse sand and gravel. This paucity of large blocks is in marked contrast with their abundance among the *nuée ardente* deposits of most volcanoes.

We cannot properly attribute this scarcity of large rock fragments to shattering during transport, for dense lava blocks would hardly be comminuted when immersed in gas-charged flows of the type in question. More likely, the magma which produced the flows rose high in the conduits and only began to froth violently when it had almost reached the surface. Instead of shattering the sides of the conduit and crater, the frothing pumice and scoria merely cored them by abrasion. Perret's masterly account of the recent eruptions of Mount Pelée gives a vivid picture of what the conditions at Mount Mazama must have been like.[8]

Finally, it should be noted that although the scoria flows usually carry more lithic material than the underlying pumice flows, the distribution of the foreign debris is otherwise quite haphazard, the fragments being thoroughly scattered throughout.

### *Erosive Action of the Flows*

Near the top of the Javanese volcano Merapi, there are places where the rock surfaces have been so severely abraded and striated by the passage of glowing avalanches that they might easily be mistaken for glaciated pavements. On the Japanese volcano Komagatake, the upper parts of the canyons were likewise swept bare by the onrush of pumice flows.

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[8] F. A. Perret, "The eruption of Mont Pelée, Martinique, F. W. I., 1929–1932," Carnegie Inst. Wash. Pub. 458, 1935.

Although there may have been vigorous erosion on the higher, now vanished parts of Mount Mazama, there are no signs that the pumice and scoria flows scratched or polished the visible slopes of the cone. There is proof, however, that they were able to sweep much incoherent material from the valley floors and to incorporate it.

The flows on the west and southwest flanks of the volcano, as noted already, did not begin to deposit their load until they reached a distance of 2 or 3 miles beyond the present rim of the caldera. About the headwaters of National, Bybee, Copeland, and Castle creeks, and to a lesser extent in the upper parts of Munson, Kerr, and Sun valleys, there is generally a transition zone between ¼ and ½ mile wide where the pumice and scoria are intimately mingled with reworked glacial debris. Where the streams have cut down to the base of the flows a similar transitional zone is exposed. Admittedly, some of this mingling may have been brought about by floods following in the wake of the first flows as they melted snow banks in their path, but most of the admixture seems to have been caused by the powerful plowing action of the heavy avalanches as they swept over incoherent moraines and fluvioglacial outwash.

### *"Fossil Fumaroles"*

Kôzu observed that for more than 6 weeks after the great explosions of Komagatake, white columns of gas rose from the surface of the pumice flows, and some of them formed small ash cones, depositing sulphur, ammonium chloride, and iron chloride at their mouths. In the area covered by the pumice fall, on the other hand, even where the deposit was more than 3 meters thick, there were neither fumes nor sublimates. The surface of the pumice flows was colored in streaks of yellow and brown, like a tiger skin, whereas that of the pumice fall was uniformly grayish white. These differences imply that the flows were much richer in gas and much hotter than the pumice fall. Measurements taken at a depth of 40 cm. below the surface showed that, in general, the temperature fell from about 350° to about 125° C. during the first 50 days. Thereafter the rate of cooling was much slower; in the next 100 days the temperature fell only from 125° to about 60° C., and during the next 640 days it fell to about that of the atmosphere. These measurements were taken on the flows where there was no special concentration of gas. But where gases were streaming off most abundantly, the temperatures were higher. At such places, temperatures of 450° and 510° C. were recorded between 8 and 11 days after the eruption, and more than 2 years later the temperatures at a depth of 40 cm. were still 99° and 60° C., respectively. Since the Komagatake pumice flows were thin and small compared with those of Mount Mazama, it cannot be doubted that the Mazama flows remained at higher temperatures for much longer periods. Being compact and almost cemented with dust, they must have been well insulated, and probably they continued to give off hot gases for many years, after the manner of the "sand flow" in the Valley of Ten Thousand Smokes.

The signs of fumarolic action within the flows are abundantly displayed near the rims of the canyons about Crater Lake. Beyond a distance of about 10 miles from the former summit of the volcano they disappear, for by the time the flows had moved that far they had lost much of their gas.

Visitors to Crater Lake entering along the valleys of Annie and Sand creeks are familiar with the spectacular columns and spires that rise from the upper part of the canyon walls. These result partly from erosion of the pumice and scoria along vertical joints, and in this sense they are analogous in origin to the "earth pillars" commonly seen in "badlands." But many occur where the pumice and scoria deposits are cut by vertical cracks the walls of which are cemented by iron oxides, kaolin, and opal. These are in fact "fossil fumaroles." Brown, pink, and white streaks cut the gray scoria where the gases rose to the surface. Some of the spires are hollow inside and have irregular openings at the top. The largest of these tubular spires is 8 feet across and may be seen near Llao's Hallway, in a tributary of Castle Creek. One of them is shown in plate 17, figure 2. All occur within the upper part of the scoria layer. On Sand Creek, as many as 150 "fossil fumaroles" may be counted in a distance of 1½ miles along the canyon walls.

Above the columns and spires, and within a few feet of the top of the flows, there is usually a distinct pink or brick-red zone, several feet in thickness. In places, particularly above the tubular openings mentioned, the pink color is intense. Where the color is deepest, pink and brown streaks lead from cracks below. It is not only in the canyons that this feature is to be seen, for all over the Pumice Desert and along Desert Creek the deposits are characterized by pink and brown blotches, the traces of thousands of fumaroles. Usually the discoloration is most marked where scoria predominates, but it may also be seen in flows of dacite pumice, as along the Diamond Lake highway above Union Creek. The reason is of course that the scoria contains much more iron than the dacite pumice, and it was the oxidation of iron-bearing gases, probably iron chlorides, that caused the pink color. Gases rising from the hot ejecta reacted with the air and percolating rains, and the level of oxidation depended largely on the porosity of the topmost materials. Usually the pink zone is at the top of the pumice-scoria deposits or a short distance above, in the overlying layer of ash. It follows that the ash must have fallen soon if not immediately after the flows had come to rest, and while they were still emitting gas.

A spectacular instance of this kind may be seen near where the Diamond Lake highway crosses the Rogue River. Here the coarse, unbedded pumice flow is overlain by fine, well bedded pumice fall up to 15 feet in thickness (plate 17, figure 3). Yet the pink, fumarolic zone occurs not within the flow, but between 3 and 5 feet from the top of the overlying bedded pumice.

When one sees these extensive signs of fumarolic action, one is tempted to imagine how the slopes of Mount Mazama may have appeared at the close of the great eruptions. The glowing avalanches had converted the glacial canyons into wide, barren plains from which, for years, plumes of acid gas rose into the air. Long after the fumaroles had almost dwindled to extinction, the plains must have been hidden by dense clouds of steam when rains fell on the hot deposits. Nothing remained of the scant forests that had formerly clothed the lower slopes of the volcano. The ridges between the plains of "ten thousand smokes" were mantled by a gray-white pall of granular pumice. The summit of Mount Mazama had gone, leaving in its place a vast caldera, 6 miles wide. Of the long glaciers which had formerly covered the upper part of the cone, only three small relics survived in the valleys on the southern slope. It would be difficult to imagine a scene of greater desolation. For an artist's reconstruction of the appearance of the mountain before and after the eruptions, see plate 18, figures 1 and 2.

## Detailed Description of the Individual Flows

Having enumerated the general features of the glowing avalanches, we may now pass to an account of the individual flows.

### *The Annie Creek Flows*

The avalanches that swept down Munson Valley into Annie Creek left no traces of their passage until they reached a point below the present Government Headquarters, approximately a mile south of the caldera rim. In this upper part of the valley, the moraines of the Munson glacier are entirely free from any cover of pumice, the presumption being that ice still occupied this region at the time of the eruptions.

Not until the pumice flows had descended approximately 5 miles from their source did they begin to deposit their load in large amount. From the Government Headquarters southward to where Munson Valley suddenly widens, the valley floor is heavily littered with hummocky glacial moraines and outwash, veneered with a broken cover of pumice and crystalline scoria. From a point due east of Annie Spring, the cover of pumice and scoria becomes continuous. At first, where the pumice is thin, the surface reflects the buried kame-and-kettle topography of the underlying moraines, but within ½ mile the hummocky surface gives place to a broad, flat plain.

There is no better or more convenient place to examine the deposits of the Annie Creek flows than at Godfrey's Glen, a short distance below Annie Spring. In the glen, three layers may easily be distinguished:

*a.* A top layer, averaging 20 feet in thickness, composed mainly of crystal-lithic ash with pumice lumps up to 6 inches across. This deposit fell from the air and is crudely bedded. Its origin is discussed on a later page.

*b.* A layer of smoke-gray scoria heavily charged with large bombs and carrying abundant crystals, particularly of hornblende.

*c.* A bottom layer of buff dacite pumice also rich in large bombs.

At the top of the smoke-gray scoria or close to the bottom of the overlying bedded ejecta, there is a discontinuous pink zone caused by oxidation of iron-bearing gases from fumaroles. In this zone, the deposits are commonly bleached and partly converted to opal and kaolin or are cemented by brown and red oxides of iron.

Generally the dark scoria layer forms between half and two-thirds of the canyon walls at this point, but its thickness varies greatly over short distances. This variation seems to imply that the scoria flow had the power of cutting its own channel in the pumice as it swept along. Some support is lent to this opinion by the fact that the dark scoria layer is nowhere found beyond the rim of the canyon, either of Annie or of Sun and Sand creeks.

There are places in Godfrey's Glen where half the scoria layer is made up of crystal-rich bombs up to 2 feet in diameter, and for each old lava fragment more than an inch across there are at least fifty of these large bombs of scoria. At such places, the total percentage of lithic fragments by volume is not more than 5. Pieces of old lava more than a foot in maximum dimension are exceedingly rare. In the finer matrix of the scoria, the proportion of lithic detritus may be considerably higher, as the diagram, figure 26, shows.

At the head of the glen, near Dewey Falls, the scoria layer descends to the valley floor, the pumice flow being absent. Farther downstream, the pumice appears beneath the scoria and both continue to thicken. Nowhere is there a clean-cut contact between the two types of flow, yet the transition zone in all places is quite thin, ranging generally between 10 and 20 feet. This sudden change in the character of the deposits, from dacite to basic scoria, deserves to be borne in mind.

In the pale pumice layer there are short and irregular brown streaks, running almost horizontally. These may signify brief periods of fumarolic activity between successive flows. There are also small lenses of reworked glacial debris within the pumice. It does not follow, however, that these were laid down during long intervals of erosion; they are more likely to have been caused by floods accompanying the pumice flows as they melted snow and ice in their path.

In many short stretches, Annie Creek has already cut through the pumice and scoria deposits to the underlying glacial moraines and bedrock lavas. Wherever the contact is exposed, it is emphasized by copious springs, the seepage line clearly defining the hummocky surface of the recessional moraines. Occasionally small pieces of carbonized wood may be collected close to the base of the pumice in Godfrey's Glen, proof that at least a few trees were growing this far up the valley before the eruptions began.

At the margin of the pumice flow, west of the main falls of Annie Creek, and at a few other places, the original level of the flow may have been slightly higher than at present. In certain parts it may have been as much as 30 feet higher. Some of these high strand lines were produced by the surge of material up slopes opposed to the direction of movement, but they also occur where upsurging would not be expected. In such instances, the explanation must be that the whole surface of the pumice flow settled as a result of compaction. Similar strand lines were observed bordering the tuff flow in the Valley of Ten Thousand Smokes.

At the falls of Annie Creek, the succession of deposits is:

*a.* 20 feet of crystal-lithic ash with a few pumice and scoria bombs up to 18 inches. Downstream this topmost layer thickens to 50 feet.

*b.* 100 feet of smoke-gray, compacted scoria.

*c.* 100 feet of pale-buff dacite pumice.

In both the scoria and the pumice, bombs more than 2 feet across are common, but fragments of old lava exceeding a few inches in diameter are rare. The nature of the finer matrix is adequately shown by the histograms, figure 26.

Below the falls, the walls of Annie Creek are cut almost entirely through massive, columnar scoria, rich in crystalline bombs (plate 17, figure 1). No clear signs of fumarolic action have been observed in this stretch of the canyon, presumably because the flows had lost much of their gas by the time they had traveled this far.

Close to the south boundary of the park, the Annie Creek flows joined those of Sun Creek, and together they swept toward Fort Klamath. Just where they came to an end cannot be determined, but probably they continued to the shores of Upper Klamath Lake, which were then many miles nearer Fort Klamath than now. Perhaps the flourlike pumice in the alluvial flats about Fort Klamath was produced by settling of finer material from the flows as they entered water.

### *The Sun Creek Flows*

From Sun Notch to the lower end of Sun Meadows, the valley floor is blanketed with hummocky glacial drift practically devoid of pumice cover. Apparently the pumice and scoria flows discharged through Sun Notch began to deposit their load only when they had passed beyond the snout of the Sun Creek glacier, 1½ miles below. The thin, patchy sprinkle of pumice on the moraines in this upper part of the valley is not a relic of the flows, but the remains of a later fall which settled on the ice and survived its melting.

Below Sun Meadows, the valley floor falls suddenly and is constricted. In this part of its course, Sun Creek has cut a gorge through glacial drift mixed with and covered by black scoria bombs and pumice. Downstream, the proportion of pumice and scoria increases, until at an elevation of about 5800 feet the two are approximately equal in amount, though still confusedly intermingled.

The first traces of fumarolic action occur about 4 miles south of the caldera rim. But nowhere on Sun Creek are "fossil fumaroles" so common as in Sand and Annie Creek canyons. The reason may be that the flows were more thoroughly mingled with glacial debris and traveled farther before dumping their load. This may also explain the absence of columnar structure and the incoherence of the scoria deposits in the canyon of Sun Creek.

In the lower reaches of the canyon, the amount of dark scoria diminishes, so that for the last 3 miles of its course in the park, the creek cuts through pumice alone, or has penetrated deeper into the underlying moraines. As the volume of scoria decreases, so do the signs of fumaroles, until in the pure pumice walls the traces of gas action can no longer be recognized.

### *The Sand Creek Flows*

A third series of pumice-scoria flows descended the southern slope of Mount Mazama through Kerr Notch. When this occurred the valley below the notch was occupied for a distance of approximately a mile by a thin tongue of ice. For ⅔ mile down the valley from the notch the hummocky moraines are covered by a light sprinkle of pale-buff pumice, probably washed in at a later date. Farther down the valley the cover of pumice thickens, but even for another ⅓ mile it is patchy and fine. Only at a distance of a mile from the notch do large lumps of pumice and scoria appear in profusion. Between 1¼ and 1½ miles from the caldera rim, the mantle of pumice and scoria begins to display the patchy red color indicative of fumarolic action. The inference seems justified that the Kerr Valley glacier cannot have extended this far.

Within the next 1½ miles downstream as many as 150 "fossil fumaroles" can be counted on the canyon walls. The gorge rapidly deepens, becoming vertical-sided, and is cut entirely through smoke-gray scoria and crystal ash overlain by 6 to 10 feet of pumice fall. Here the red, oxidized layer close to the top of the canyon wall is very pronounced, and the scoria begins to show a large-scale columnar jointing that becomes more marked at lower elevations. Despite the fact that the gorge is cut largely in basic scoria, the surface of the plain into which it is incised is covered only with the buff pumice flow or with the overlying pumice fall. Accordingly, the scoria flow must have been confined, as in other canyons, to a central and narrow depression.

Close to the confluence of Wheeler and Sand creeks lies the area known as the Pinnacles, undoubtedly the theater of the most intense fumarolic activity within the park. Here the canyon reaches a depth of more than 200 feet and its walls are sculptured into clusters of slender pillars. Many of the pillars are traversed by vertical cracks along which the scoria has suffered from fumarolic action, being compacted by iron oxides or by the deposition of opal and kaolin. In a few pillars, long tubular channels lead upward to circular openings at the top. These mark the passageways of rising gases, to the oxidation of which we must ascribe the red layer which follows the top of the scoria deposit and extends upward a few feet into the overlying ash.

The threefold layering of the deposits at the Pinnacles is clear from the photograph (plate 16), the white and buff pumice layer at the base contrasting vividly with the dark scoria above, and this in turn with the overlying bedded ash on the rim of the canyon. In more detail, these three layers consist of:

1. Top layer of fine ejecta, 6 to 10 feet. A sample from this layer contains little material more than 1 mm. in diameter; only 1 per cent consists of fragments between 0.5 and 1 mm.; 20 per cent is between 0.25 and 0.5 mm., the remainder being dust less than 0.25 mm. in diameter. Excluding the dust fraction, the remainder has the following percentage composition by volume: pumice and scoria, 44; lithic chips, 32; feldspar, 17; ferromagnesian crystals, 7. Though a third of the separable fraction consists of rock particles, the total content of such material in the deposit is probably much less than one-fourth, since by far the bulk of the fine dust is made up of pulverized pumice, scoria, and crystals. That the ejecta in this topmost layer fell from the air can hardly be doubted in view of their stratification.
2. The smoke-gray scoria layer, averaging approximately 80 feet thick. This is made up of bombs of crystal-rich, basic scoria up to 2 feet across, set in a finer matrix of pulverized scoria. Fully 90 per cent of the fraction larger than 5 mm. consists of scoria; the remainder is made up of old lava fragments. Despite the large size of the scoria bombs, few of the lithic pieces exceed even an inch across. In the finer fraction of the deposit, the content of lithic detritus is considerably higher, making up 18 and 23 per cent of the volume of two samples examined. Most of the lithic chips lie in the size range 1 to 5 mm., few occurring in the fraction less than 0.5 mm. As compared with the underlying dacite pumice, the scoria layer is generally much richer in crystals, particularly in ferromagnesian minerals. Moreover, though pyroxene predominates among the dark minerals of the pumice, hornblende predominates in the scoria. In some samples, between one-third and one-fourth of the fraction below 5 mm. in diameter is made up of crystals. How thorough the comminution of the scoria must have been is amply shown by the fact that of the material measuring less than 5 mm. in diameter, more than half consists of dust less than 0.5 mm. across.
3. The bottom layer of dacite pumice, also averaging approximately 80 feet in thickness. Lithic detritus makes up on an average approximately one-fourth of the volume of material less than 5 mm. in diameter, but in the entire deposit the content of such detritus is only about 10 per cent. By far the bulk of the lithic material lies in the size range 2 to 5 mm.

   Of the fresh magmatic material in the deposit, bombs of pumice up to 2 feet across form between 5 and 10 per cent of the volume, the remainder consisting of pulverized pumice, much of it in the form of impalpable dust, and crystals, among which feldspar far predominates over pyroxene.

Beyond the park boundary, the smoke-gray scoria layer disappears, though many scattered bombs of scoria may be found close to the Dalles-California highway. Whereas the earlier pumice flow continued for many miles, the later scoria flow spent itself soon after reaching the flats at the base of the volcano.

From the histogram, figure 22, it will be seen that in the pumice flow near Sun Pass, approximately 40 per cent of the material less than 10 mm. in diameter measures less than 0.5 mm. Here the volume percentages of pumice, old rock, feldspar, and heavy minerals in the size range 0.25 to 10 mm. are respectively 65.7, 24.9, 8.2, and 1.2. When the coarser material is also considered, the total volume of lithic material is reduced to between 10 and 15 per cent by volume, for among the fragments more than an inch across fully 95 per cent consists of pumice. The largest lithic fragments measure 3 inches across.

We may now briefly follow the course of the Sand Creek pumice flows after they deployed onto the plateau east of Mazama. Such was their mobility and momentum that they rushed onward for another 12 miles. In their path lay Boundary Butte. Up the onset slope of this obstacle they surged for 200 feet, carrying lumps of pumice 2 feet in diameter. Swirling round this and the neighboring buttes, the flows then emptied into the canyon of Williamson River, near the present site of the village of Kirk. In doing so they must, for a time, have choked the outflow of water from the Klamath Marsh. When the channel was cleared, great quantities of pumice were carried downstream into Upper Klamath Lake.

In the vicinity of Boundary Butte, the pumice deposits are marked by flat-topped benches 20 to 30 feet above the general level. The road running northwest from Kirk passes through a hollow between such benches. How they were formed is not clear. Either the deposits were channeled by floodwaters in the wake of the flows, or, more likely, the benches resulted from successive waves of pumice.

### *The Rogue River Flows*

The glowing avalanches that followed the Rogue River and its tributaries united near the confluence with Union Creek, and the composite flow continued for another 20 miles to a point 1½ miles above the present site of the village of McLeod. The snout of this composite flow thus lies 35 miles in an air line from the former summit of Mount Mazama.

The following notes refer to the deposits found along the Rogue River from the vicinity of Diamond Lake to McLeod; the flows that ran down the tributaries of the Rogue are described in a later section. Although most of the flows of basic scoria which poured down the north slope of Mount Mazama through the depression between Llao Rock and Grouse Hill came to an end in the Pumice Desert, the earlier and more voluminous flows of pumice not only crossed the desert but surmounted the divide beyond, and some of them discharged into Diamond Lake. The bulk of the pumice then separated into two branches, one directed eastward toward the Klamath Marsh and the other westward down the valley of the Rogue. The latter branch was joined by flows which skirted the west side of Desert Ridge. As far down as the junction with National Creek, the deposits of the Rogue valley consist of buff and pale-gray dacite pumice unusually poor in lithic debris. In many places the river has cut through the deposits to the underlying basalts, as at the Upper Falls and in Hamaker Meadows. The great scarcity of charcoal among the ejecta in this region implies that this part of the Rogue River valley supported only a scant cover of trees at the time of the eruptions.

Where Copeland Creek enters the Rogue, the thickness of the pumice increases to almost 200 feet. Still farther south, the thickness continues to increase and locally approximates 300 feet. Along this stretch of its course, the river has cut through the deposits to the underlying intracanyon olivine basalts. Here also the pumice deposits are abundantly charged with burned wood. On the west bank of the river, a mile below the crossing of the Diamond Lake highway, Smith discovered at the base of the pumice an 8-foot stump of a cedar tree, 3 feet in diameter, standing upright in the position of growth. Its upper part was thoroughly charred, but the lower part, perhaps because of quick burial, was burned only a little. This is the only example known of an upright tree within the pumice flows. The rest of the charred wood occurs as scattered limbs and logs lying more or less prostrate. Some of them measure between 2 and 3 feet across, but by far the majority are only a few inches in diameter. Hemlock, cedar, and lodgepole pine occur sparingly, but most of the wood belongs to the white- and sugar-pine group. Clearly the forests, though less dense, were otherwise like those now living in these parts.

Mention should be made here of the splendid sections exposed along the Diamond Lake highway south of the Rogue River bridge. At this locality, the coarse, unbedded lump pumice is overlain by fine, well bedded pumice up to 15 feet in thickness (plate 17, figure 3). About ½ mile below the bridge, the deposits of the pumice flow are cut by a channel 7 feet deep and 50 feet wide, filled with stratified, granular pumice that must have been washed into place (plate 19, figure 1). Noteworthy is the much greater proportion of lithic detritus in this upper, bedded pumice (see histogram 360, figure 25). In these exposures the pink layer produced by oxidation of fumarolic gases is to be found, not at the top of the pumice flow, but between 3 and 5 feet from the top of the bedded ejecta. Presumably, therefore, the pumice showers fell on the flow while it was still giving off gas, for if they had fallen long after, the pink layer would be found at the top of the flow, as it is in the roadside sections nearer Union Creek, where the overlying stratum of bedded ejecta is absent.

Close to the confluence of the Rogue with Bybee and Castle creeks, the thickness of the pumice flow rapidly diminishes, for thereabouts the pre-existing valley was wider and the flow spread over a broader front. The nature of its finer constituents is shown in the histogram, figure 25. None of the dark scoria flows that swept down Castle Creek reached this distance, nor did any of the scoria flows that entered via National, Copeland, and Bybee creeks. As for the lithic fragments in this part of the flow, it is extremely rare to find pieces more than an inch long, though many of the bombs of pumice exceed 2 feet across.

For the next 10 miles down the Rogue River, as far as Prospect, most of the pumice flow has been removed by erosion. The presence of pumice benches 100 feet above the river clearly shows that a great volume has been carried away. Apparently the flows here spread over broad basaltic flats in a series of braided tongues. Some of these overflowed the valley of the Rogue, crossed Mill, Barr, and Red Blanket creeks, and poured into the valley of the Middle Fork (see map, figure 16), where they accumulated to a thickness of 250 feet. Near the Upper Power House on the Middle Fork, the flows coming from the north cascaded into the gorge, eddied upstream for a mile, and piled against the south bank. Checked in their rush, they then turned westward and plunged into the deep gorge of the Rogue below Prospect.

Mention may be made in passing of the thick deposits of bedded and reworked pumice along the South Fork of the Rogue. Clearly these cannot be related to the flows under discussion, for a high ridge separates the Middle from the South Fork, across which it would have been quite impossible for the flows to pass. Nor can the deposits be related to the pumice fall immediately preceding the flows, for the South Fork drains an area beyond the limits of that fall. The deposits were therefore derived by downwashing of older pumice, possibly products of the same eruptions that left the coarse ejecta in the Pumice Flat at the east base of Union Peak.

The branching tongues of the pumice flow, having diverged below Union Creek, converged again at Prospect, where they tumbled into the main canyon of the Rogue. This they followed for another 8 miles. Along this stretch of the river most of the deposits have been washed away, but there are many places where pumice benches are still preserved. Near the Prospect Power House, for example, there are benches 150 feet above the river, and at Laurelhurst, a few miles lower, there are benches 100 feet above the river. These indicate the original thickness of the flows at those points. Not until the flows reached the junction of the Rogue with Cascade Creek, where the main river leaves its basaltic gorge and enters an older and broader valley through the Western Cascades, were they able to spread out again. Here their remains form wide flats 50 to 80 feet above the river.

Suddenly the flows come to an end, 1½ miles above McLeod. Fortunately a roadside quarry and deep road cuts offer excellent opportunity for study of these terminal deposits. These show, as might be expected, an extremely high content of fine pumice dust. The flows had traveled so far, and the larger pumice lumps had been so reduced in number and size by internal explosions and mutual bombardment, that much of the material was reduced to powder. Whereas half the material in the flows above Union Creek may be composed of pumice bombs more than an inch across, the proportion of such bombs at the snout of the flows rarely exceeds 10 per cent. A sample from the roadside quarry near the snout shows the following content by volume: less than 0.5 mm., 70 per cent; 0.5–1 mm., 8 per cent; 1–3 mm., 13 per cent; 3–5 mm., 3 per cent; 5–10 mm., 3 per cent; and greater than 10 mm., 3 per cent. Moreover, the content of lithic fragments is much less than in the flows nearer the source, and few exceed even 1 mm. in size. In a second sample from the same quarry, 41 per cent of the material was less than 0.125 mm. in size, and all fragments larger than 5 mm. were composed of pumice. Though lithic material made up 16.7 per cent of the fraction between 0.125 and 5 mm., the total lithic content in the deposit was only about 6 per cent. Histogram 361, figure 25, shows the nature of the finer constituents. Finally, it should be added that charcoal logs, some of them 3 feet across, are almost as plentiful at the snout of the flows as anywhere higher up the valley of the Rogue.

The choking of the Rogue River gorge by a mass of pumice up to 150 feet in thickness must have produced extensive floods. Much of the pumice must have been swept downstream immediately and more has since been removed. Accordingly, terraces of washed pumice occur far below the snout of the flows. For instance, an excavation along the roadside close to the Rogue-Elk junction shows reassorted, bedded pumice about 50 feet above the level of the river (plate 19, figure 2). Pumiceous sand and gravel border the river at least as far down as the Agate Desert, near Medford.

### *The Castle Creek Flows*

The avalanches that descended the southwest flank of Mount Mazama left scarcely any trace of their passage until they reached the base of the steep slopes about 2 miles beyond the rim of the caldera. Only when the flows had reached the valley of Castle Creek, between the opposing slopes of Mount Mazama and Union Peak, was their speed sufficiently checked to permit large-scale deposition. Of all the pumice flows from Mazama, none contains such a large proportion of coarse material. Even 12 to 15 miles west of Annie Spring there are places where half the deposits consists of pumice lumps between 3 and 12 inches across.

Just as at the heads of Munson, Sun, and Kerr valleys, so at the head of Castle Creek, there is a broad transitional zone in which the amount of glacial drift gradually diminishes downstream as that of pumice and scoria increases. For more than 2 miles, the valley floor is cut through the recessional moraines which underlie the pumice. Much of the finer glacial debris was incorporated in the basal parts of the pumice flows as they scoured the surface of the moraines. Indeed, the flows churned up the surficial glacial deposits to a depth of several feet, and doubtless this admixture was accentuated by floods accompanying the flows.

The pumice flows of Castle Creek traveled 18 miles before they joined the flows of the Rogue River valley. They were prevented from spreading northward by a high ridge of lava, but southward they overflowed the gorge of Castle Creek and spilled into the valley of Union Creek, which they filled to a maximum depth of 250 feet. Pumice bombs up to 2 feet across are common, but few lithic fragments exceed ½ inch in average diameter. The total content of foreign fragments approximates 5 to 8 per cent. It must be emphasized, however, that there is wide variation in the coarseness of the deposits over short distances. Locally bombs more than an inch across may make up half the total volume; elsewhere fine dust is by far the principal constituent.

Though the pumice flows spread all the way down Castle Creek, the later scoria flows did not extend far beyond the park boundary, a distance of little more than 7 miles from the source. Moreover, as in other canyons, the scoria flows were confined to a central and narrow depression in the earlier pumice deposits. It is among these scoria deposits that the only "fossil fumaroles" of Castle Creek are to be found, and they are almost restricted to the part of the canyon above the junction of Castle with Whitehorse Creek. Here the dark scoria deposits have been carved into the spectacular gorge known as Llao's Hallway, a chasm narrow enough in places to be spanned by outstretched arms, yet 200 feet deep (plate 15, figure 2). Farther downstream, the scoria deposits are characterized by curved joints that favor the development of large caves. Here also the deposits are traversed by vertical joints defining triangular and quadrangular columns from 6 to 10 feet wide and as much as 100 feet in height.

Above the unbedded scoria lies a layer of crystal-rich ash up to 30 feet in thickness, within which is the pink zone due to oxidation of fumarolic gases that rose from the hot mass of scoria.

### *Other Flows down the West Slope of Mazama*

The flows directed through the depression between Llao Rock and Hillman Peak left only a patchy cover of material on top of the hummocky glacial moraines between the rim of the caldera and the headwaters of National Creek. Apparently most of the flows which passed across this part of Mazama were made up of basic scoria and crystal-rich ash. In the canyon of National Creek the deposits are mainly composed of gray scoria and ash, mixed in the upper stretches with abundant glacial debris. The flows had traveled 10 miles before they tumbled into the canyon, and it is not surprising that they had lost much of their heat and gas and therefore show no signs of fumarolic action.

The flows directed down the west slope between Hillman Peak and the Watchman found their way into the glacial valleys of Copeland and Bybee creeks, though for a distance of about 3 miles beyond the caldera rim they left scarcely any trace of their passage. Indeed, most of the fine ejecta thinly sprinkled on these upper slopes of the volcano was probably laid down after the flows had passed beyond.

In the upper parts of both Copeland and Bybee canyons most of the deposits left by the flows consist of incoherent gray scoria and ash, much admixed with glacial material. Farther down the canyons, the scoria gives place to the older dacite pumice, which continues downstream to the confluence with the Rogue River. Lumps of pumice as much as 18 inches across are not uncommon, though pieces of old lava rarely measure more than 4 inches. The total content of lava fragments amounts to between 5 and 10 per cent of the whole.

### *Flows down the North Slope*

On the north side of Mount Mazama there were no deep glacial canyons to concentrate the flows. The consequence was that once they had passed through the gap between Red Cone and Grouse Hill, they spread out in wide sheets. The momentum of the earlier pumice flows was enough to carry them across the basin of the Pumice Desert and over the saddle to the north, but the later scoria flows failed to escape from the desert in that direction. Consequently the surface of the Pumice Desert consists chiefly of crystal-rich scoria and ash, among which lie many bombs. One of these measures 12 by 12 by 3 feet, but most of the others are less than a yard across. Many are exceptionally rich in hornblende, and the fine ash is crowded with glistening prisms of this mineral. Despite the large size of the bombs and the proximity to the source, fragments of old lava more than ½ inch in diameter are notably rare. What the volume of the pumice and scoria deposits is in the Pumice Desert there is no means of determining accurately, though their thickness may well be 200 feet. The pronounced red and pink blotches revealed by road cuts through the upper part of the scoria show that fumaroles must have been abundant and long-lived in this region. A well drilled adjacent to the highway where it crosses the lowest part of the desert passed through 106 feet of smoke-gray, hornblende-rich scoria without penetrating the underlying white dacite pumice. Samples consist almost entirely of lithic fragments and discrete crystals of feldspar and hornblende. With these are much less numerous crystals of pyroxene, and a little brown glass. The content of lithic fragments increases, though not regularly, with depth. Near the bottom they are far more abundant than crystals. An interesting deduction may be drawn from these observations. Although the Pumice Desert is thickly covered by ejecta, particularly in its central part, it still has the form of a shallow basin. Hence, a deep valley must have existed there before the final eruptions of Mount Mazama began. Yet when the first glowing avalanches of dacite pumice swept across the valley they did not convert it into a flat plain. Instead they rushed across with such vehemence that they left it much as it was and continued over the divide to the north. The later avalanche of scoria and crystals lacked either the momentum or the mobility of the dacite avalanche, for little of it escaped across the northern divide. Most of it came to rest in the valley itself, and some made its way out via Desert Creek and so continued to the plateau beyond.

The earlier pumice flows raced onward to Diamond Lake. Exactly what happened when they reached the lake can only be conjectured. This much, however, seems certain: the flows passed across the lake and made their exit down Lake Creek. They followed this for 5 miles before splitting into two branches at Toolbox Meadows, one branch turning westward to empty into the valleys of Lava and Clearwater creeks, while the other continued down Lake Creek and joined the North Umpqua River. An enormous volume of coarse pumice must thus have been discharged into the North Umpqua, and much of it was washed downstream for many miles. Between 25 and 30 miles below Toketee Falls, there are banks of washed pumice including lumps 6 inches across; about 20 miles below the falls, near Panther Leap, the tops of the pumice banks lie 20 feet above the river. In many places, these washed deposits carry charred logs.

It may be argued that all the pumice north of Diamond Lake must have been washed into place by rivers, that it would have been impossible for the flows to cross a body of water 3 miles in length. Yet the flows did somehow traverse the lake, for the deposits bordering Clearwater Creek show no trace of stratification. Had they been washed thus far by streams, they would surely show bedding, and the pumice lumps would show considerable rounding. Moreover, the deposits carry logs of charred wood that lie at random, and in places they are characterized by the pink color indicative of fumarolic action. They must therefore have been hot and gas-charged when they came to rest. Not until the flows had traveled approximately 10 miles beyond Diamond Lake did they lose their own propulsive force. Presumably, when the first onrush of pumice entered the lake, the light ejecta remained on the surface, forming a blanket across which the later waves of pumice poured as if on dry land. How else could they have retained their heat and gas?

Though much of the pumice that crossed Pumice Desert poured into Diamond Lake, and much of it, as we have seen, turned westward into the valley of the Rogue, the most voluminous flows were deflected eastward through the depression between the slopes of Mount Thielsen and Timber Crater. These flows crossed a low saddle in the crest of the Cascade Range and continued for another 20 miles, as far as the site of the present village of Chemult. Their total journey from the source was therefore more than 30 miles, though the slopes down which they moved were extremely gentle. The buoyancy and mobility of the mass was such that at Beaver Marsh, 6 miles from the snout of the flow, the deposits carry many bombs of pumice up to 6 feet across, and one as much as 14 feet in maximum dimension.

In the vicinity of Chemult, near the margins of the flows, the coarse, unbedded lump pumice is overlain by fine pumice, much of which is almost pure glass dust (histogram 252, figure 21). East of Beaver Marsh, on the road to Willow Spring, fine crystal-lithic ash and pumice lie on the deposits of the flows as well as on the older pumice fall beyond. These ejecta probably represent the settling of the finer constituents which rose in swirling clouds near the margins of the flows.

### *Flows down the East Slope*

In the valley northeast of Roundtop and in Bear Valley there is no difficulty in distinguishing the deposits of the pumice fall from those of the flows which followed, for the former consist of pale, granular dacite and cover the valley sides, whereas the latter are confined to the valley bottoms and consist mainly of basic scoria and crystal ash. In the upper parts of both these valleys, the scoria cover is thin and patchy. Only below Cascade Spring on Bear Creek, 1½ miles from the caldera rim, are thick deposits of pumice and scoria to be found. The pumice flows, as usual, traveled a much greater distance than the scoria flows, for the latter only reached the base of the volcano, whereas the pumice spread for another 10 miles to the edge of Klamath Marsh.

Glowing avalanches also poured down the canyons east of Mount Scott, uniting with the Sand Creek flows in wide-fronted floods that emptied into the marsh. The water level in the marsh may have been higher than now, for at the head of Wocus Bay there are water-worn lumps of pumice between 20 and 30 feet above the present level. Of course the water level may not have been that much higher than at present, for the discharge of tremendous volumes of pumice into the marsh must temporarily have raised the level, and the flows, entering the water at great speed, must have caused powerful waves capable of carrying pumice lumps far up the opposite shore. Much of the pumice, after entering the marsh, escaped down the Williamson River, but most of it, after floating a short time, probably sank to the bottom.

### Volume of the Pumice-Scoria Flows

Little difficulty was experienced in calculating the volume of the pumice fall, for the base of the deposit is exposed in many places and the thickness is easy to determine elsewhere by excavation. The pumice and scoria flows, on the other hand, were voluminous enough to obliterate much of the pre-existing topography and convert deep glacial valleys into broad plains. Locally, rivers have cut through the deposits and exposed the moraines and lavas below. From these known thicknesses and by making reasonable assumptions as to the form of the buried parts of the glacial valleys, it is possible to calculate the volume of pumice and scoria in the principal valleys.

On the plateau east of Mount Mazama, the topography offers little evidence concerning the thickness of the ejecta. Fortunately, several wells were drilled by the Southern Pacific Company along their tracks in this region, a few were drilled in Chemult and elsewhere for local residents, and three were drilled for the purposes of the present study, so that we now have a fairly accurate picture of the form and character of the pre-pumice surface. Between the base of Mount Mazama and the Klamath Marsh, this pre-pumice surface was a broad piedmont plain sloping eastward. Here and there low knolls of basalt rose above the general level, but for the most part the surface consisted of volcanic sands and gravels laid down by streams draining the eastern slopes of Mount Mazama. The following data concerning the pumice and underlying deposits are relevant in the present connection.

Close to the snout of the pumice flow at Chemult several wells have yielded records. One, drilled for the Great Northern Railroad in 1932, revealed these data: 0–41 feet, pink pumice; 41–62 feet, clay; 62–68 feet, ash; 68–180 feet, interbedded hard and soft clay; 180–223 feet, basaltic lava.

In the village of Chemult itself, six wells provided logs. The thickness of the pumice ranges between 34 and 45 feet. In all, the topmost pumice is extremely fine, to a depth varying from 20 to 25 feet. Beneath this, the pumice is heavily charged with large lumps. Apparently the coarse lump pumice represents the pumice flow proper, and the overlying fine ejecta represent material that settled from the air after the flow had come to rest. In some wells the pumice was found to rest on red clay; in others it rests on basaltic sand and gravel; in one at least it is underlain immediately by vesicular basalt.

Approximately 6 miles south of Chemult, at Diamond Lake Station (formerly Lonroth) on the Southern Pacific Railroad, the pumice is 65 feet thick and rests on at least 96 feet of stratified sand, gravel, and clay. Near by, in the hamlet of Beaver Marsh, a well penetrated 73 feet of pumice without reaching bottom.

At Yamsay Station, approximately 5 miles farther south on the Southern Pacific tracks, the pumice is 53 feet thick. A mile or so northwest of this station, at the junction of the Dalles-California highway with the Diamond Lake highway, the pumice is reported to be 114 feet thick and to rest on "black sand."

At Lenz Station, 9 miles south of Yamsay, the pumice is 65 feet thick and rests on sand and gravel. At Fuego, approximately another 9 miles to the south, two wells were drilled, one 500 feet and the other 136 feet west of the station. The former penetrated pumice to a depth of 70 feet without reaching the underlying bedrock; the other passed out of pumice and entered sand at a depth of 55 feet.

At Kirk Station, close to the south margin of the avalanche deposit, the pumice is 47 feet thick and rests on so-called "chalk rock," probably Pliocene diatomite.

There are few available records of wells drilled through the pumice flow east of the Southern Pacific Railroad. On the Fordyce or Ryan Ranch, a short distance south of Lenz Station, three wells penetrated the deposits and entered coarse sand at depths between 18 and 30 feet. Farther east, near the Old Military Crossing, on the edge of Klamath Marsh, the pumice flow is 66 feet thick and is underlain by massive basalt. According to George Hartley, wells sunk near the center of Klamath Marsh pass through layers of pumice interstratified with sediments even to a depth of 350 feet. Doubtless these thin pumice layers represent products of much earlier eruptions.

In order to determine the thickness of the pumice and scoria flows closer to the base of Mount Mazama, three wells were drilled west of the Dalles-California highway. The first was 1 mile south of the northwest corner of the Klamath Indian Reservation, at an elevation of 4700 feet. Down to a depth of 80 feet the well passed through smoke-gray pumice and scoria, rich in crystals and small lithic fragments. Approximately 10 feet from the surface, the ejecta were stained bright pink by fumarolic action. From 80 to 93 feet, the well penetrated white lump pumice; from 93 to 96 feet, it traversed water-worn volcanic sand and gravel.

A second well, 5 miles to the south, passed through the following layers: 0–5 feet, crystal-lithic ash with fine pumice; 5–20 feet, pink dacite pumice; 20–80 feet, pumice mixed with smoke-gray scoria and crystal ash; 80–121 feet, coarse white dacite lump pumice; 121–125 feet, pumice-free volcanic sand and gravel.

The third well was sunk 8 miles farther south, near the bank of Scott Creek, approximately 3/5 mile west of the Dalles-California highway. In the upper part of this well, the smoke-gray scoria and pumice were abnormally rich in small lithic fragments, to such an extent in fact that certain layers contained as much as 75 per cent of such ejecta. From 50 feet down to 75 feet, basic scoria was absent and lithic fragments were rare. In this range, the ejecta consisted almost entirely of coarse dacite pumice lightly mixed with crystals. From 75 feet to the bottom of the well at 100 feet, there were rapid alternations of fine, granular pumice and water-worn volcanic sand. Presumably, therefore, the base of the pumice-scoria flows may here be placed at 75 feet; the underlying deposits represent the products of older pumice eruptions mingled with river-borne sediment.

We are now in a position to make an estimate of the volume of the pumice-scoria flows. First, consider the area east of the park. From the foregoing well logs, and taking into consideration the probable pre-pumice form of the valleys that debouch from the park onto the plateau to the east, it may be calculated that approximately 4 to 4.5 cubic miles of material were laid down by the glowing avalanches. How much pumice escaped from the Klamath Marsh into the Williamson River and so was washed into Upper Klamath Lake cannot be determined.

Within the limits of the park, the volume of the pumice-scoria flows, prior to erosion, approximates 1 cubic mile. In the valley north of Timber Crater and in the depression bordering Diamond Lake and Lake

Creek, the volume may be about 0.6 cubic mile. In the valley of the Rogue River down to the Union Creek junction, and in National, Copeland, Bybee, and Crater creeks west of the park boundary, the total volume is estimated to have been 0.75 cubic mile prior to erosion. Finally, between the Union Creek junction and the snout of the Rogue River flow near McLeod, the original volume must have been close to 0.3 cubic mile, whereas in the valley of Annie Creek south of the park boundary there may have been approximately 0.2 cubic mile of pumice. What can never be known is the amount of pumice that was washed into the Upper Klamath Lake below Fort Klamath, and the amount that was carried down the Rogue River below McLeod. It is likely, however, that this missing volume was not great.

The total volume of the pumice and scoria flows is therefore about 7 cubic miles. Almost certainly, it is not less than 6 nor more than 8 cubic miles. Of this volume, at most 20 per cent consists of old lithic detritus. In other words, of the 17 cubic miles that disappeared from the top of Mount Mazama, only a small fraction is to be found in the deposits of the glowing avalanches. The proportion of lithic detritus in the preceding pumice fall is even less. The significance of these figures in connection with the origin of the caldera needs no emphasis.

## The Last Weak Explosions

After the pumice and scoria flows had been discharged, most of the energy of the volcano was spent. Nevertheless, enough gas remained in the magma chamber to cause a few dying explosions.

The concluding eruptions cannot have been violent, for the ejecta are fine and limited in distribution. Most of the material was blown above the vents and dispersed by winds, just as the initial deposits of pumice were scattered. But unlike the earlier pumice fall, the final fall contains few large lumps of pumice, and is much richer in both lithic fragments and crystals. Probably most of the pumice blown out by these last explosions represents material that fell back into the craters during the first explosions, to be hurled out a second time. Much of the ejecta consists of dark-brown and reddish crystal-rich scoria and small fragments of old lava. The high content of lithic detritus is only to be expected, for after the great pumice and scoria explosions the conduits must have been greatly enlarged and their walls must have been subject to inward slumping.

Most of the ejecta fell near the caldera rim, especially on the northeast side, where they form banks up to 50 feet in thickness. Some material was blown westward and may be seen resting on top of the pumice flows along the Rogue River (plate 17, figure 3). Compared with the earlier pumice falls, the youngest ash is much finer, better sorted, and richer in crystals and lithic fragments. Typical samples are represented by the histograms (figure 21, Rugged Crest; figure 25, no. 360; figure 26, nos. 230*c*, 36*a*).

The fine ash overlying the pumice-scoria flows in the canyons of Castle, Annie, Sun, and Sand creeks cannot be a product of these eruptions, for it is restricted to the central parts of the valleys. For this reason, it is interpreted as the result of settling of the finer constituents that rose into the air as the avalanches swept down the valleys. The thickness of such ash locally reaches 50 feet, but is usually between 5 and 20 feet. It fell immediately or soon after the flows came to rest.

Similar in mode of origin is the fine glass dust which overlies the pumice flows near Chemult. No scoria flows reached this far from the source, and consequently there is no crystal-rich ash; on the other hand, there must have been violent turbulence at the snouts of the pumice flows, and great clouds of fine glass dust must have risen into the air, to settle slowly on the coarse deposits.

The volume of the final "ash" fall is probably of the order of 0.25 mile.

## Total Volume of Material Erupted during the Culminating Activity of Mount Mazama

It remains to consider how much magma was evacuated from the reservoir beneath the volcano, and how much old rock was torn from the sides of the conduits and from the top of the mountain during the climactic activity.

The following table summarizes the results obtained.

| | Volume (cu. miles) | Crystals (%) | Rock fragments (%) |
|---|---|---|---|
| Pumice fall | 3.5 | 10–15 | 3–4 |
| Glowing avalanches | 6–8 | 20–25 | 15–20 |
| Final "ash" fall | 0.25 | 40 | 40 |

The total volume of material laid down is thus between 9.75 and 11.75 cubic miles. Of this amount, between 1.65 and 2.62 cubic miles consists of crystals and between 1.10 and 1.84 cubic miles of old rock.

Using approximate figures for the sake of convenience, we may say that 11 cubic miles of ejecta were deposited, including about 2 cubic miles of crystals and 1.5 cubic miles of old rock fragments. The remaining 7.5 cubic miles are composed of frothy pumiceous and scoriaceous glass.

Exactly how much liquid magma is represented by the glass is uncertain. The vesicularity of the pumice varies considerably; allowance must be made for the pores between the fragments; and there is no means of determining how vesicular the magma itself was prior to eruption. Certainly, if all the pumice and scoria were remelted to bubble-free liquid, its volume would be reduced by much more than half. Hence, it seems safe to say that at most 3 cubic miles of actual liquid were emptied from the reservoir beneath the volcano.

The final estimates are consequently as follows:

| | |
|---|---|
| Volume of liquid magma erupted | At most 3 cu. miles |
| Volume of crystals erupted | Approx. 2 cu. miles |
| Volume of lithic fragments | Approx. 1.5 cu. miles |
| Total | Approx. 6.5 cu. miles |

Vast as this total is, it is still much less than half the volume of Mount Mazama that has disappeared. How then did the caldera originate?

# The Origin of the Caldera

Except Diller, all who have studied Crater Lake agree that the destruction of the summit of Mount Mazama occurred either during or immediately after the great pumice and scoria eruptions just described. Had the caldera been formed before these eruptions, the bottom and sides would be covered by ejecta and the floor would be marked by large vents. Eruptions of the magnitude of those we have discussed have never been known to originate within a large caldera, for once a caldera is formed, the energy of a volcano is largely or entirely spent. Caldera formation on composite volcanoes is usually a sign of exhaustion.

### How Much of Mount Mazama Has Disappeared?

The area of the caldera enclosed by the rim is approximately 27 square miles. Its original depth is a matter for conjecture. Parts of the floor of the Krakatau caldera have settled more than 200 feet since 1883. Conceivably, the floor of Crater Lake subsided several hundreds of feet as the residual magma in the reservoir contracted by crystallization.

Assuming that the depth of the caldera from the rim varied between 1500 and 3500 feet, and allowing for the configuration of the bottom, the volume of the original depression must have been of the order of 12 cubic miles.

To this must be added the volume of the lost portion which rose above the caldera rim. If a peak 12,000 feet high existed immediately before the final eruptions, the additional volume to be accounted for would be about 8 cubic miles, less the volume of the summit crater or craters and the volume of the glacial cirques on the sides. The volcano may already have been reduced in height, however, by collapse at the time of the pumice eruptions which preceded the dacite flows from the Northern Arc of Vents. If the summit was lowered at that time, the amount of reduction cannot have been large. Even supposing that the top had been lowered as much as 2000 feet, the volume of the cone would not have been diminished by more than a cubic mile.

We conclude, therefore, as Diller did on other grounds, that approximately 17 cubic miles of Mount Mazama disappeared to form the present caldera. Only three explanations are possible: first, the top of the volcano was removed by explosion; second, it collapsed; third, these processes were combined.

### Diller's Collapse Theory

Diller felt convinced that Crater Lake was formed by engulfment. He argued that if 17 cubic miles of rock had been blown out by explosions, a layer of coarse fragmental debris more than a thousand feet thick would have been formed in the immediate vicinity. Even if the ejecta had been more widely scattered, there would still be an enormous accumulation near the source. He could find no trace of such a deposit. Instead, he noted, as Dutton had, that glaciated surfaces and moraines are exposed in many places beyond the caldera rim and that elsewhere they are covered by a thick blanket of pumice. He decided, further, that the pumice was erupted long before the destruction of the top of Mount Mazama.

Failing to see evidence of an explosive origin, he looked, though in vain, for positive arguments in support of the collapse hypothesis. He thought, erroneously, that the Cleetwood dacite flow was erupted during the engulfment and that part of it poured "backward" down the caldera wall. Like Dutton, he regarded the absence of arcuate fault blocks and curved fissures beyond the caldera rim as a difficulty in the way of the subsidence theory. To account for their absence, he postulated gradual, piecemeal foundering from the center outward. Moreover, being aware that engulfment demands withdrawal of magma from depth in sufficient volume to make room for the part that collapses, he pictured the formation of rifts far down the flanks of Mount Mazama and the eruption from these rifts of 17 cubic miles of lava. Nowhere was he able to find the lava for which he sought. Subsequent surveys have shown that no such voluminous flows occur anywhere in this region.

Diller was thus forced to adopt the collapse theory on negative evidence, namely, the absence of an adequate volume of fragmental debris in the vicinity of the caldera.

### Smith and Swartzlow's Explosion Theory

For more than thirty years, Diller's opinion passed unchallenged. In 1936, Smith and Swartzlow advanced the radically different view that the top of Mount Mazama was destroyed by explosions of unusual violence, during which 17 cubic miles of the original cone were removed by blasts from within. So revolutionary was their opinion that it seems advisable to discuss their principal arguments in some detail.

1. Their main reason for adopting the explosion theory was the belief that Diller had grossly underestimated the amount of old debris on the outer flanks of the volcano. It seemed to them that the mantle of pumice conceals vast quantities of coarse, blocky detritus, ample in fact to account for the missing part of the mountain.

This conclusion can no longer be entertained. A thorough study of the products of the final eruptions shows that only about 1½ cubic miles of lithic detritus were removed from the summit of the volcano. The remainder consisted of *new magma* in the form of pumice, scoria, and crystals erupted from the underlying reservoir. In the canyons on the outer slopes of the mountain, these ejecta rest directly on old lava flows or on unmistakable glacial moraines. Nor is there any trace of a layer of lithic detritus beneath the vast sheet of granular pumice which encircles the volcano. Here and there along the caldera rim a thin layer of coarse fragmental material does separate the pumice from the underlying lavas, but this is far from being the general rule. More than half a mile from the rim there is no hint of such a layer. Even on the brink of the caldera, blocks of old lava more than 3 feet across are surprisingly rare; in the pumice and scoria flows lithic fragments larger than 3 inches in diameter are extremely few; in the earlier pumice fall, only occasional fragments measure more than 2 inches in diameter. Surely an explosion of such gigantic proportions as to remove 17 cubic miles of solid rock must have left behind great piles of much coarser debris.

Observation of the distribution of the products of the culminating eruptions and analysis of their lithic content therefore leads us to accept with confidence the original views of Diller and Dutton. There is not nearly enough old lithic material among the ejecta to warrant the belief that Mount Mazama was decapitated by explosion.

2. The suggestion has been made that glacial and stream erosion may have removed much of the lithic debris. Even if this were true, the estimate that only 1½ cubic miles of lithic material were erupted was based on the assumption that the present canyons had not been cut. Since the caldera was formed, a few thousand years ago, streams have cut narrow box canyons through the pumice flows, but apart from this the removal of ejecta has been insignificant.

3. A third argument was advanced against Diller's collapse theory, namely, the absence of lava flows commensurate in volume with the part of the volcano which has disappeared. The absence of such flows cannot, however, be held to substantiate the opposite view of explosion. Removal of support necessary to cause foundering of the summit of a volcano may be brought about in other ways, as by deep-seated intrusion, or by rapid draining of the underlying reservoir by colossal eruptions of pumice. What is important is that the reservoir be so far evacuated that its roof can no longer stand.

4. Kilauea, which all admit to be a collapse caldera, differs from Crater Lake in several respects, notably in the presence of arcuate fault blocks along the margins. This difference should not be construed as an argument that the two depressions are of different origin. At Kilauea, the lavas involved are fluid and have built a low, broad shield. Repeated rise and fall of magma within the central conduit and related fissures is responsible for the familiar curved step faults on the margins of the sink. Mount Mazama, on the contrary, was a steep-sided composite cone, and its collapse was almost certainly a single paroxysmal event. Hence it displays features comparable with those of Krakatau, Santorin, Aso, and other calderas on composite cones. Around these, circumferential fault blocks are conspicuous by their absence.

5. Until recently it has generally been stated, though without adequate discussion, that most calderas of the Pacific region are of explosive origin. Elsewhere,[1] in a detailed review of the caldera problem, prepared as a basis for the present study, arguments have been presented to show that few volcanic depressions more than a mile across are caused simply by explosion. Volcanologists in New Zealand, the East Indies, and Japan are now unanimous in the opinion that large calderas are primarily the result of engulfment.

6. Smith and Swartzlow regard the shape of Crater Lake and the nature of the materials in its walls as support for the idea of explosion. They point to the presence of a quantity of pyroclastic ejecta interbedded with the lavas as proof that Mount Mazama was built largely by explosive activity. Not only has the volume of such debris been exaggerated, but even if the entire cone were composed of such ejecta, it would not follow that the caldera itself was a product of explosion. Many composite volcanoes rich in pyroclastic deposits and some cones wholly composed of fragmental debris have collapsed to form calderas.

Comparison of the form of calderas 5 or 6 miles across with forms caused by artificial explosions has little value. To produce a caldera of the size and shape of Crater Lake by explosion, the explosive charge must be of exceptional strength. To produce the necessary gas pressure, the magma generating the gas must lie at great depth. If the magma lies close to the surface it cannot hold much gas in solution; the roof of the chamber may then be shattered by mild explosions, and the crater will probably have the shape of a wide-flaring funnel. In order to blow out 17 cubic miles of solid rock and leave a vast steep-walled caldera, the magma must lie far below. Eruptions would then blow out, not only much of the old cone, but great quantities of the underlying basement rocks. Yet at Crater Lake practically all the lithic fragments were derived from the andesite and dacite flows of Mount Mazama itself. A few pieces of olivine-bearing basic andesite and basalt and still fewer chips of pre-Pliocene lava are the only fragments torn from the basement. Accordingly, the top of the magma chamber lay not far beneath the surface. Presumably, it lay above the present floor of Crater Lake.

Thousands of denuded volcanoes have been examined all over the world, yet the remnant necks rarely exceed a mile in diameter, and the larger ones were caused by the coalescence of several vents and by a combination of explosion and collapse. The absence of denuded volcanic necks even approaching a third the diameter of Crater Lake is in itself a powerful argument against the explosion theory.

To return to the evidence offered by the form of Crater Lake, it may be recalled that usually explosion craters are funnel-shaped, especially if the walls are composed of fragmental deposits. Cylindrical craters have been cored by strong blasts of gas, as at Vesuvius in 1906, but these are relatively small. The singular paucity of lithic detritus round Crater Lake, Krakatau, Santorin, and similar calderas shows that coring of cylinders miles across is possible only in theory. Precipitous walls bordering large volcanic depressions must be taken as a sign of engulfment.

7. The concluding arguments of Smith and Swartzlow relate to the post-caldera eruptions of Wizard Island. That a volcano may resume activity after the collapse of its summit is only to be expected. Neither the subsequent activity nor the character of the material erupted has any bearing on the mode of origin of the caldera itself.

From the foregoing, the conclusion is inescapable that Crater Lake cannot have been formed by explosive shattering of the top of Mount Mazama. We may now pass to a preferred explanation which is fundamentally different. In this explanation, we begin with the knowledge that only a small fraction of the 17 cubic miles of solid rock which have disappeared is to be found as fragments among the ejecta.

## A Preferred Theory

Throughout most of its history the magma erupted by Mount Mazama was hypersthene andesite. Eruption of diverse types of magma following prolonged outpouring of intermediate magma is almost invariably a sign of decadence in a volcano's history. During the culminating eruptions, pumice and scoria were emptied from the magma chamber in unprecedented volume. First the dacitic, upper part of the chamber was drained; then followed large volumes of the underlying basic magma. Altogether, approximately

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[1] Howel Williams, "Calderas and their origin," Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 25, pp. 239–346, 1941.

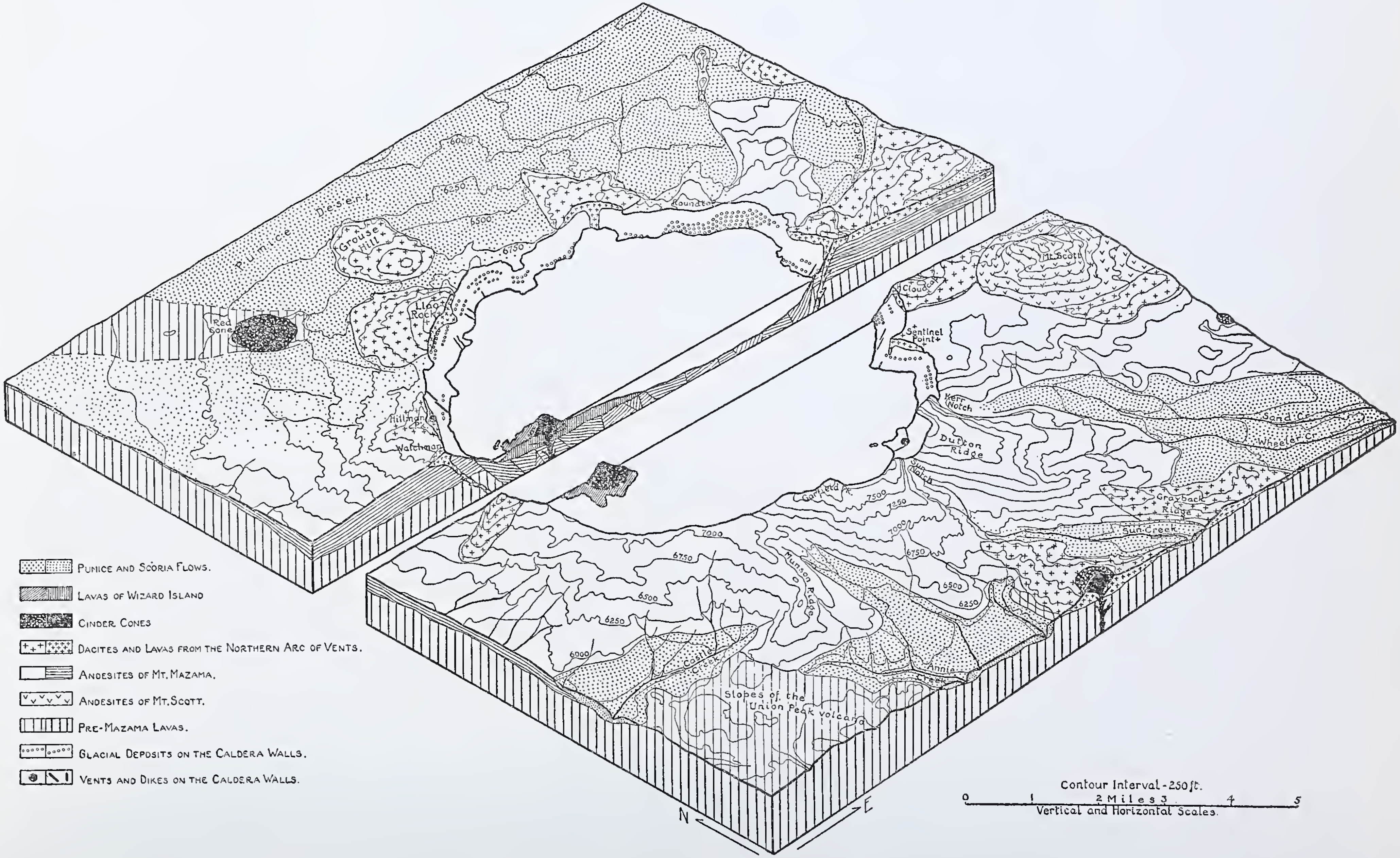

Fig. 27. Block diagram of Crater Lake, looking northeast

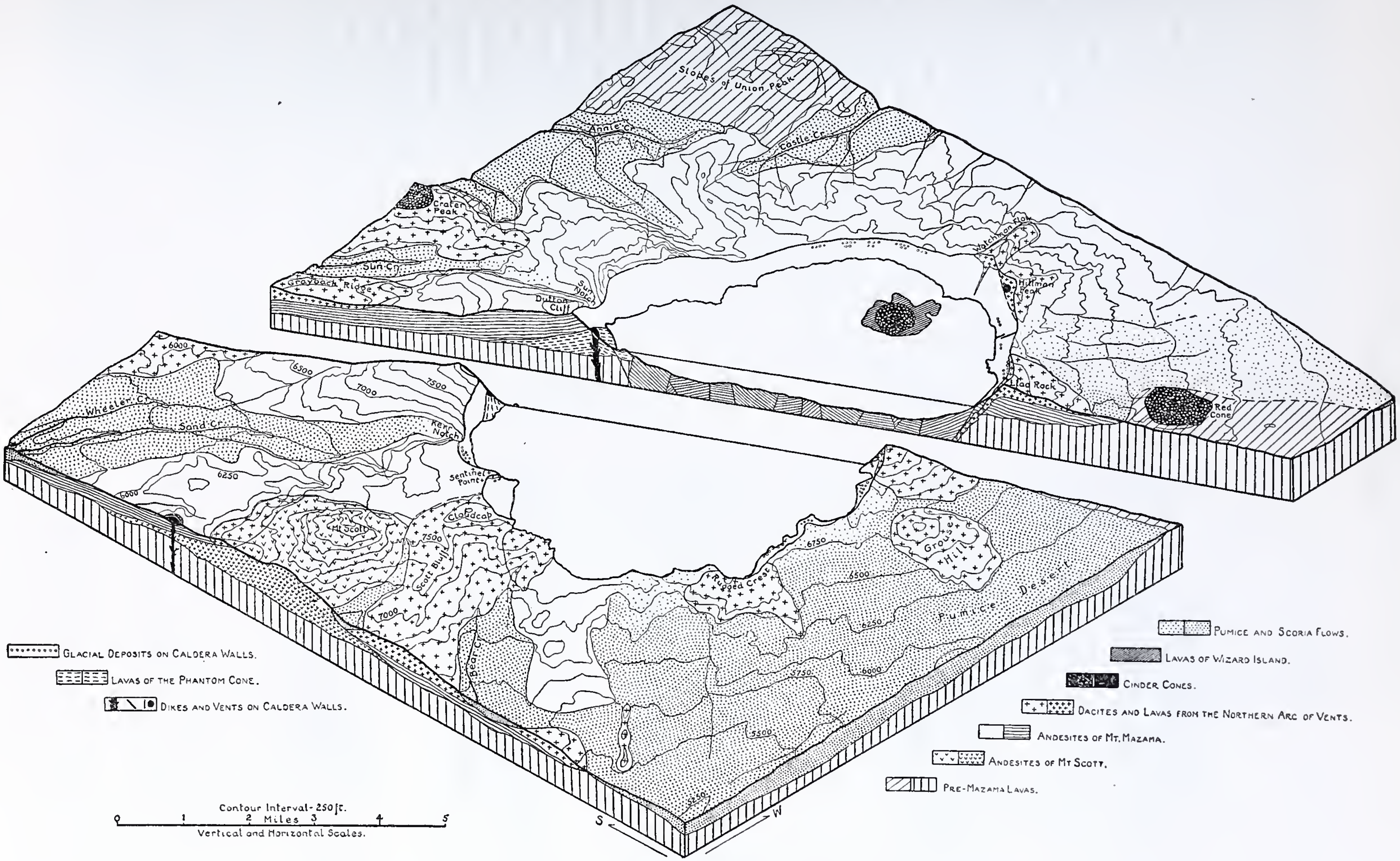

Fig. 28. Block diagram of Crater Lake, looking southwest

5 cubic miles of crystals and liquid escaped, carrying with them approximately 1.5 cubic miles of old rock, torn from the mountain top. This was not a long-continued process; possibly the whole eruptive episode may have lasted only a few weeks or months. It may have been as brief as the activity preceding the destruction of Krakatau. Clearly, if this great volume of magma was erupted in so short a time, the magma chamber cannot have been replenished from below at the same rate. Accordingly, a potential or actual void must have been created in the upper part of the magma chamber. No longer supported by the pressure within, the roof must then have collapsed, carrying with it the summit of the cone (see figures 27, 28, and 29).

This, however, is not the entire story. Seventeen cubic miles of rock disappeared to produce the caldera. At most 1.5 cubic miles of this disappeared by explosion; another 5 cubic miles caved into the magma chamber to replace the liquid and crystals erupted. What happened to the remaining 10.5 cubic miles? That they must also have vanished by engulfment cannot be denied. We are therefore left to seek a cause.

Many years ago, Stübel urged the importance of withdrawal of magma beneath volcanoes as an explanation of calderas. Distracted, as we are bound to be, by spectacular surface manifestations of volcanic energy, we are apt to forget the equally important intrusive history at depth, for this is seldom revealed except by long-continued erosion. Lately, the brilliant studies by Bailey, Richey, and their associates among the denuded volcanoes of the Western Isles of Scotland and by Stearns on Oahu have served to focus attention on the complex and wide-spreading intrusions which take place far below the surface. The roots of ancient volcanoes commonly reveal a maze of intersecting dikes. Occasionally, underground migration of magma culminates in fissure eruptions far down the flanks of a volcano, as at Kilauea in 1924.

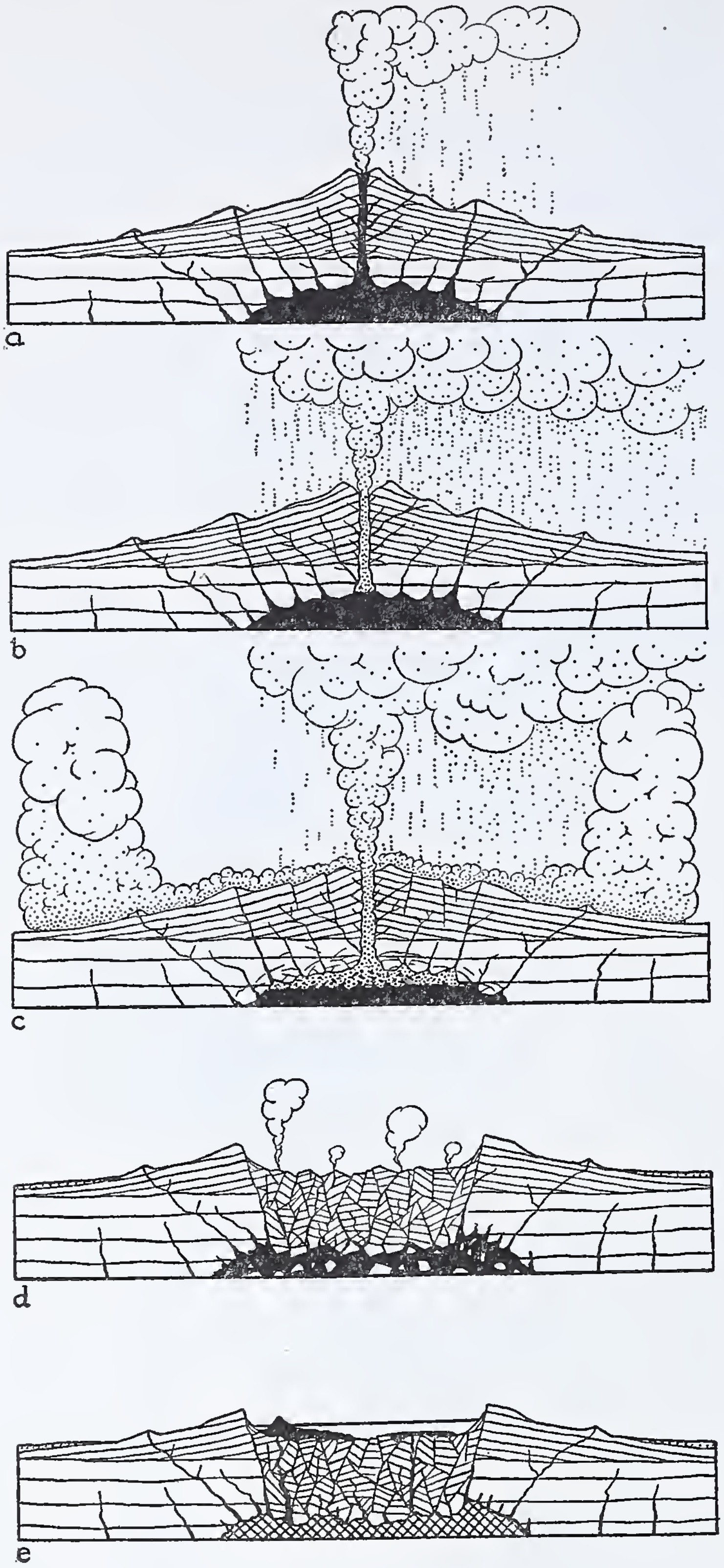

Fig. 29. The evolution of Crater Lake:

*a.* Beginning of culminating eruptions. Magma high in conduit; mild eruption of pumice.

*b.* Activity increases in violence. Showers of pumice more voluminous and ejecta larger. Magma level lowers to top of feeding chamber.

*c.* Activity approaches the climax. Combination of vertically directed explosions with glowing avalanches (*nuées ardentes*). Chamber being emptied rapidly; roof commencing to fracture and founder. Magma also being drained from the chamber through fissures at depth.

*d.* Collapse of the cone as a jumble of enormous blocks, some of which are shown sinking through the magma. Fumaroles on the caldera floor.

*e.* Crater Lake today. Post-collapse eruptions have formed the cone of Wizard Island and probably have covered parts of the lake bottom with lava. Magma in the chamber largely crystallized.

More generally, perhaps, such migration results in concealed intrusions, and only when these are large are they reflected by engulfment at central craters.

Measurements of tilt have demonstrated that volcanoes rise and fall in sympathy with movement of buried magma. The entire edifice of Kilauea seems almost to breathe in response to underground displacements of magma. Jaggar's painstaking researches at this volcano have shown that "*sudden* downward phases are just as common and rhythmic as *gradual* risings, and this introduces a whole world of magmatic force, magmatic earthquakes and magmatic intrusion in pulsating stresses through time, where down-go and opening of voids must be granted."[2] Slow accumulation of magmatic pressures followed by quick release is the natural rhythm of volcanoes. The opening of radial fissures on the slopes of large volcanic cones is much less likely to be caused by hydrostatic pressure of magma in the narrow central conduits than by a general doming of the roof of the magma chamber following increased pressure from below.

At times of vigorous magmatic movement, volcanic cones are often subject to stresses adequate to open far-stretching rifts. Tension fractures produced by upsurging magma and openings caused by withdrawal of liquid provide pathways for migration. The central pipe of a volcano is only one of countless channels. Since it leads to the summit vent, what happens there may be plainly observed; nevertheless the events witnessed in the crater may be only incidental to more fundamental movements far below, along channels far removed from the central pipe. Already we have seen that during the later stages of the history of Mount Mazama, a semicircular arc of vents opened on the northern flank, probably along a ring fracture. Presumably this fracture resulted from withdrawal of magma at depth and consequent breakage of the chamber roof. Again, we have noted that during its late history, Mount Mazama developed linear groups of parasitic cones and domes on its flanks. Some of these are disposed on radial fractures, developed as tension fissures during times of uprising magma. It seems reasonable to suppose, therefore, that during the long interval of quiet preceding the climactic eruptions of Mazama, internal pressures may have accumulated until they were able to rupture the walls of the magma chamber in many directions. The time of maximum magmatic pressure is not during eruption, but precisely the moment preceding the first explosion. It is then that fracturing of the walls and injection of dikes are most likely to occur.

Recent studies by Jaggar, Stehn, van Bemmelen, and Reck, to mention only a few, all point to the importance of engulfment. Jaggar, whose lifelong experience at Kilauea gives unusual weight to his opinion, strongly advocates the idea of engulfment as the prime cause of calderas. During the explosive activity of Kilauea in 1924, the pit was enormously enlarged. Yet the volume of old rock thrown out was only 1/253 of the volume which disappeared by engulfment. "The great steam-blast eruptions of the world," he writes,[3] "have been accompanied by what Mercalli called '*sprofondamenti*,' deepenings by collapse." Referring to the destruction of the ancient summit of Vesuvius and the consequent formation of Monte Somma, unreasonably described by most writers as the result of decapitation by the great Plinian eruptions of A.D. 79, he adds:

> The tremendous event of the Vesuvian crisis, when a steam-blast eruption happens, is a "*sprofondamento*," a deepening. The amount of surface lava, dust and rocks is trivial compared to crateral evacuation.
>
> But the notion that such a volume as the contents of Monte Somma was left by the single evacuation of the Pompeiian eruption, is as fantastic as that Niuafoou crater was completely made in 1886.
>
> The total volume of everything poured out and blown out of Vesuvius from 79 A.D. to the present would scarcely change the profile of the volcano.

Imposing as they may be, the eruptions accompanying caldera formation may be of quite secondary importance as compared with the underground flow of magma into dikes and sills.

Unfortunately, few attempts have been made to compare the volumes of calderas with those of the surrounding ejecta, and it is therefore seldom possible to say how much engulfment was caused by explosion and how much by concealed intrusion. The volume of the great depression containing Lake Toba in

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[2] T. A. Jaggar, letter, September 11, 1940.

[3] T. A. Jaggar, "Origin of Crater Lake cup," Volcano Letter, Hawaiian Volcano Observatory, No. 451, September 1937.

Sumatra is, as van Bemmelen has shown, approximately equal to that of the tremendous sheet of pumice which encircles it. Hence, as he suggests, the collapse may properly be attributed to expulsion of magma at the surface. At Krakatau, Katmai, and Santorin, much of the ejecta fell out to sea, and accurate estimates of the volume are therefore impossible. At Crater Lake, fortunately, the conditions for measurement are ideal.

Obviously, to dispose of 10.5 cubic miles of magma to make room for the part of Mount Mazama not accounted for by engulfment into the space provided by eruption of pumice and scoria, far-reaching fissures must have opened at depth. If these fissures had opened near the roof of the magma chamber, the consequent intrusions would have caused a broad domical uplift of the entire volcanic edifice. Physiographic evidence of such an uplift has not been recognized. If, on the other hand, dike fissures opened at much greater depth, perhaps parallel to the general trend of the Cascade Range, there may have been little or no surface effect in the surrounding region. Swarms of subparallel rifts undoubtedly underlie the High Cascade chain of volcanoes, and it requires no stretch of the imagination to suppose that these may have been reopened or that new ones may have been formed to drain magma from the chamber beneath Mount Mazama. Stearns'[4] careful mapping of the denuded volcanoes of Waianae and Koolau on Oahu has shown the presence of literally thousands of subparallel dikes elongated along the major axes of those inverted-canoe-shaped domes. Presumably similar swarms of dikes, following lines of tectonic weakness, underlie the shields of Kilauea and Mauna Loa.

Is there any evidence that the formation of Crater Lake was preceded by extensive internal assimilation of the cone, like that which took place at Katmai? Enlargement of a magma chamber by solution of the walls and roof cannot of itself produce a caldera, but it must accentuate any tendency to collapse by thinning the roof and widening its span.

Only under special circumstances can the hybrid character of a magma be definitely determined. Fenner has given adequate reasons for supposing that much of the cone of Katmai was dissolved by rhyolitic magma prior to and during the eruptions of 1912 which led to the formation of the summit caldera. The ejected pumice clearly betrays a dual origin. Dark streaks of andesite stand out conspicuously in the pale rhyolitic matrix, and crystals from the andesite are scattered throughout the rhyolitic glass. According to Fenner, rapid assimilation occurred chiefly, if not entirely, within the actual crater. Had assimilation proceeded slowly and at depth, the hybrid melt might well have lost the recognizable marks of its twofold origin.

If assimilation occurred inside Mount Mazama, the rocks affected were mainly hypersthene andesites of the cone itself and perhaps also some of the underlying olivine-bearing basic andesites. But seven-eighths of the magma erupted during the final eruptions consists of dacite pumice. The remaining eighth consists of basic scoria. Hence, if much of the interior of Mount Mazama was dissolved, the solvent must have been an acid magma.

A considerable interval of rest preceded the culminating explosions. This much is indicated by the violence and scale of the eruptions themselves, and by the fact that trees were growing on the moraines far up the sides of the volcano. During this interval of quiet the process of assimilation may have gone on until not only were the rising magma and its dissolved constituents thoroughly mixed, but the hybrid melt itself may have undergone gravitative differentiation into an acid, dacitic upper portion and a crystal-rich basic fraction below. Hence, perhaps, the absence of semidigested fragments among the ejecta. Positive proof that the magma chamber was enlarged by assimilation before the culminating eruptions began seems to be entirely lacking.

One more problem calls for discussion, namely, the remarkable paucity of large blocks of old lava among the products of these climactic eruptions. Their scarcity among the deposits of the first eruptions, that is, among the pumice fall, may be due simply to the fact that the initial eruptions, though they hurled out several cubic miles of granular pumice, were not powerful enough to dislodge large fragments of solid rock from the walls of the conduit and crater.

The scarcity of large blocks among the deposits of the later *nuées ardentes* admits of no such ready explanation. Surely avalanches strong enough to rush

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[4] H. T. Stearns and K. N. Vaksvik, "Geology and ground-water resources of the island of Oahu, Hawaii," Division of Hydrography, Territory of Hawaii, Bull. 1, 1935; Bull. 2, 1939.

40 miles from the source, carrying pumice bombs several feet in diameter, had power to sweep huge blocks of old rock for long distances beyond what is now the rim of the caldera. The *nuée ardente* deposits of Mount Pelée and Montserrat are heavily charged with blocks many miles from their point of origin.

If extensive collapse and insliding had taken place around the summit vent while the glowing avalanches escaped, large blocks would have been caught in the upsurging, frothy magma and have been swept along in the dense clouds of pumice and compressed gas. It does not seem likely, therefore, that crumbling and caving of the sides of the crater and conduit occurred in the manner observed at Kilauea during the steam-blast eruptions of 1924. Perhaps coarse detritus may have slid into the vent between the major eruptions, to be finely triturated by intervening eruptions of moderate intensity. Perhaps, on the other hand, the vents never were clogged with blocky detritus and the small lithic fragments found in the pumice-scoria deposits were torn from the sides of the conduit by the abrasive action of the upsurging, effervescing magma. This interesting problem must be left unsolved.

The air of mystery that still hangs over Crater Lake may never be wholly dispelled. Concerning these conclusions, however, there is reasonable assurance:

1. The caldera was not formed by the explosive shattering of the top of Mount Mazama. Of the 17 cubic miles of old rock that disappeared, approximately 1.5 cubic miles were removed by explosion, and even this fraction was mainly erupted in small fragments.
2. The volume of pumice and scoria blown out during the culminating eruptions, when recalculated as bubble-free liquid plus crystals, amounts to approximately 5 cubic miles.
3. The summit of Mount Mazama was engulfed by withdrawal of magmatic support from below. This withdrawal was caused partly by rapid eruption of pumice and scoria from the upper part of the magma chamber, but principally by injection of magma at greater depths, probably into swarms of fissures.
4. Prior to the formation of the caldera, conditions for engulfment were at hand, for a semicircular ring fracture had already been formed on the northern flank of the cone, and the roof of the magma chamber lay at shallow depth.
5. When the collapse took place, it was eccentric with respect to the former summit of the volcano. Hence, the center of the caldera lies well to the north of the former peak. This eccentric engulfment was determined by the pre-existence of the Northern Arc of Vents.
6. The collapse was probably as cataclysmic as that of Krakatau, and presumably it occurred in a few gigantic steps, the inner parts of the cone foundering first.

# Comparison of Crater Lake with Other Calderas

Among shield volcanoes of Hawaiian type, calderas result from drainage of the central conduits by copious outflow of lava from fissures far down the flanks or by widespread intrusion at depth. Support is thus removed from beneath the central, summit vent, the walls of which then founder along arcuate fractures. For instance, the pit of Halemaumau on Kilauea was greatly enlarged during the steam-blast eruptions of 1924. Yet only an insignificant fraction of the enlargement was produced by the actual eruptions; the enlargement resulted almost entirely from collapse induced by withdrawal of support as the lava level in the principal conduit was lowered by submarine flows escaping from fissures on the sides of the shield.

In composite volcanoes built of more siliceous ejecta, collapse and caldera formation may likewise be brought about by dike injection at depth, but perhaps more generally it results from drainage of the magma chamber by colossal eruptions of pumice and scoria.

The history of Crater Lake is closely paralleled by that of Krakatau. The famous outbreak of this volcano began in May 1883. At first, the eruptions were mild. Pumice was hurled above the vents and settled in showers under the control of the wind. During the culminating eruptions of August 26–28, the pumice escaped so rapidly that most of it fell in the neighborhood of the vents in the form of glowing avalanches, almost identical in character with those which swept down the canyons around Crater Lake. In all, 18 cubic kilometers of material were blown out. Of this, only about 5 per cent was composed of old lava fragments torn from the sides of the original cones. The remainder was new magma evacuated from the chamber below. This sudden drainage of the reservoir brought about collapse, and it was the foundering of the old cones into the sea that propelled the devastating tidal waves which killed 36,000 natives on the shores of Java and Sumatra. The form of the caldera floor bears the unmistakable imprint of this mode of origin. No funnel-shaped explosion vents were formed, but in addition to the caldera itself deep submarine troughs were produced leading out from the margins along lines of tectonic weakness. Forty-four years of quiescence ensued. In 1927, a new basaltic cinder cone, Anak Krakatau, rose from the floor of the caldera, just as Wizard Island rose within Crater Lake.

The history of the Santorin caldera is much the same. Before the caldera was formed, between 1800 and 1500 B.C., the island of Santorin was a complex of overlapping cones, like Mount Mazama. A long period of quiet preceded the climax. Here again, the first eruptions were mild. The inhabitants of the island had time to escape and their buildings remained intact. As the eruptions continued, they became more violent. Of all the material erupted, only 1 per cent consisted of old rock fragments; the rest came from the magma chambers. Obviously, therefore, the formation of the caldera was not caused by explosive shattering of the old cones, but by collapse. Engulfment was controlled partly by the positions of the original cones, for the scalloped margin of the caldera is determined by concentric fractures about separate vents. Just as Cleetwood Cove and perhaps Grotto Cove, on the edge of Crater Lake, lie on the sites of former vents, so do the semicircular coves along the edge of the Santorin caldera. Collapse was also controlled, as at Krakatau, by radial zones of weakness, and by regional, tectonic lines which determined the roughly rectilinear outline of the caldera. Fifteen hundred years elapsed before renewed activity began on the caldera floor. In 197 B.C., a dome of dacite rose from the sea. Since then, several other domes have risen at long intervals, the last during the years 1925 to 1928.

The great calderas of Japan, particularly those of Kyushu, also owe their origin to engulfment following copious eruptions of pumice and tuff. Lake Taupo and other lakes on the North Island of New Zealand are clearly related to crustal foundering along tectonic lines following immense outpourings of rhyolite tuff from swarms of fissures. So are the great lakes along the Barisan rift zone in Sumatra. It is the absence, near all these calderas and volcano-tectonic depressions, of an adequate volume of old, lithic detritus that explodes the explosion hypothesis.

# The Caldera Floor

The bottom of Crater Lake is hidden from view over an area of approximately 20 square miles. To obtain a clear picture of its form it would be necessary to make many more soundings than are now available. Nevertheless, the records collected by Dutton's party in 1886 and by the naturalist staff of the Park Service during the seasons 1938–1940 suffice to indicate the principal features (see map, figure 30). What is now most needed is a series of closely spaced soundings along radial lines within a mile from shore, in order to determine the presence or absence of marginal fault scarps.

The following are among the principal features revealed by soundings:

1. The sides of the caldera are steep. In many places the hidden slopes are steeper than the cliffs above the water's edge. Except near Wizard Island and along the south side of the caldera, the walls drop at least 1000 feet within ½ mile of the shore.

2. Not only are the sides of the basin steep, but most of the floor lies more than 1500 feet below the level of the lake. Before Wizard Island was formed, more than three-quarters of the floor may have been that deep. In other words, by far the greater part of the original bottom may have lain more than 3500 feet below the highest point on the rim.

3. The deepest part of the caldera lies northeast of the center. Here, in an area measuring 2 by 1½ miles in maximum dimensions, the soundings exceed 1900 feet. Over most of this deep area the floor is surprisingly flat. Perhaps it was in this region that activity was first renewed after the formation of the caldera, and it may be that a lava lake existed there for a time.

4. Much of the shallow floor near Wizard Island is covered by post-caldera lavas erupted from fissures at the base of that cone. Possibly some of these flows extend 2 miles east of the island, almost to the center of the lake. Within the 500-foot contour, where the soundings are most numerous (figure 30), the surface of the submerged lavas seems to be as rugged as that of the lavas exposed above water. Among lavas of this type, the snouts of successive flows are generally both high and steep. Yet there are places on the submerged flows and along their margins where the surface falls with unusual rapidity. For instance, in one locality the surface falls 311 feet within a distance of 500 feet; in another, the drop is 235 feet in less than 200 feet. Such high, steep slopes can scarcely be the fronts of blocky lavas; more likely they mark fault scarps. If so, Wizard Island may have been built on a platform above the general level of the caldera floor.

5. Diller inferred that, in addition to the cone of Wizard Island, two other cones exist within the caldera. Additional soundings disprove this view. About a mile south of Pumice Point, a conspicuous prominence rises from the caldera floor. Its summit lies only 661 feet below the level of the lake. Approximately 1000 feet to the north, the floor falls to 1521 feet. These slopes are much too steep to be the sides of cinder or lava cones, and presumably they indicate a large fault block or horst left standing during the differential foundering which produced the caldera. Halfway between this supposed horst and Pumice Point there is a depression 1700 feet deep, but until more soundings are made, it is impossible to say whether this marks the site of an explosion vent or of a sunken fault block.

The foregoing appear to be the principal features of the caldera floor. The question now arises, Do they shed any light on the origin of Crater Lake? Unfortunately, post-caldera eruptions have seriously modified the configuration, and the floor has probably suffered local subsidence owing to cooling and contraction of the underlying body of magma. The answer to this question, therefore, cannot be conclusive. Nevertheless, such evidence as the soundings provide strongly favors the theory of collapse. Had the summit of Mount Mazama been destroyed by explosion alone, the original floor of the caldera would be marked by one or more large explosion vents. It would be marked also by many cones of blocky ejecta, and

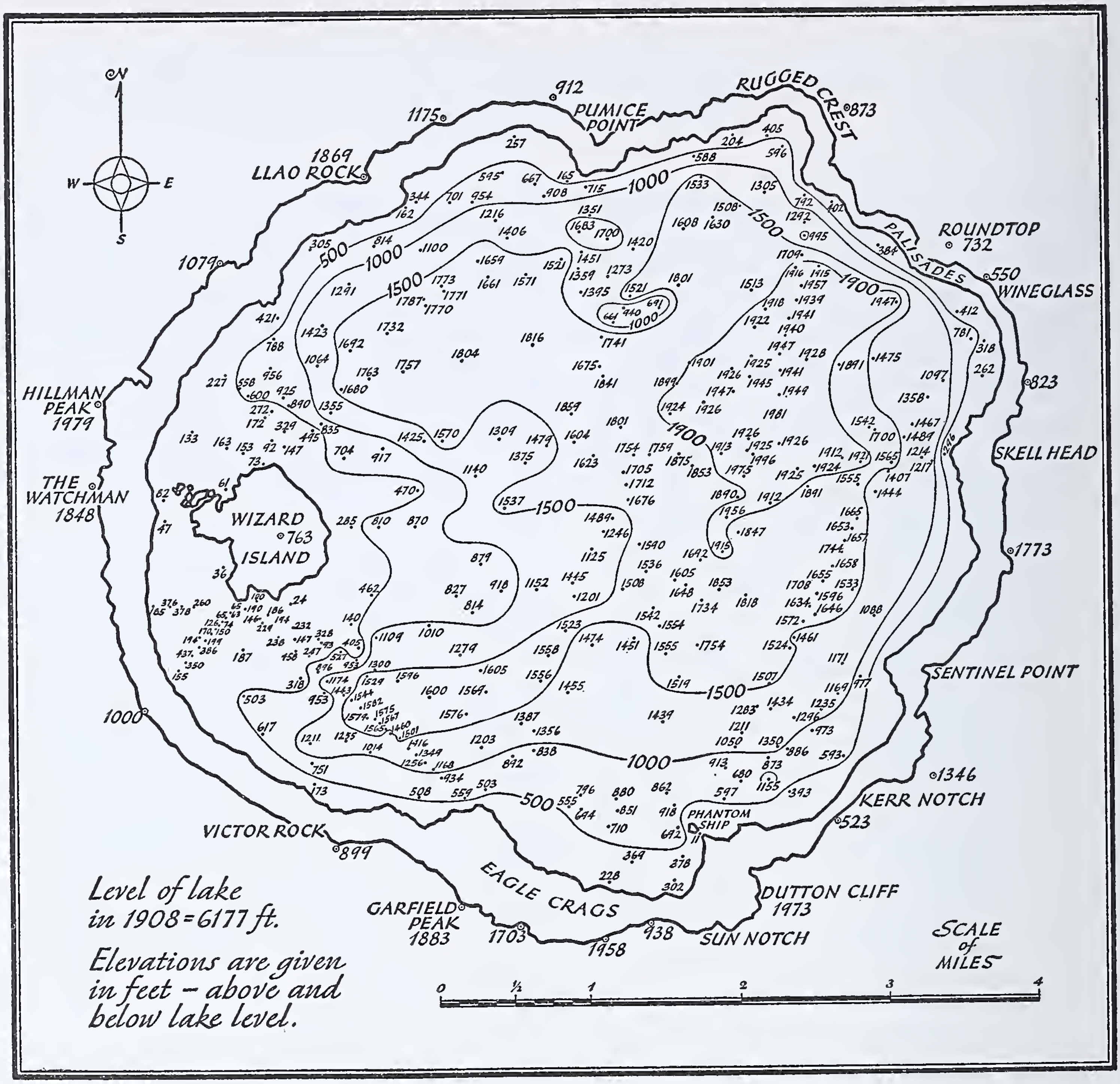

Fig. 30. The floor of Crater Lake. Based on soundings by the original Dutton survey and by the park naturalist staff, 1937–1940. (Drawn by A. W. Severy.)

the walls would be bordered by imposing slides of talus. Yet the soundings reveal no such cones, and there is a conspicuous paucity of talus beneath the margins of the lake. If it be answered that the cones and talus have been buried by upbuilding of the caldera floor, then even more than 17 cubic miles of Mount Mazama must have been removed by explosion. The futility of this argument has already been discussed.

If the form of the caldera provides no support for the explosion theory, does it offer positive as well as negative evidence in favor of the alternative theory of collapse? Some geologists will allow that the steepness and height of the walls are in themselves a positive argument, and some will accept the evidence of soundings for the existence of submerged fault scarps. Some will point to the large, flat-topped bench overlooking Chaski Bay as a landslide block caught, as it were, in the act of engulfment, for the lavas composing the bench dip lakeward and they must have slid to their present position from a level several hundreds of feet higher up the caldera wall (plate 19, figure 3). Yet there is no denying that even if the caldera was formed by explosion, insliding of the walls and later faulting of the floor may well have occurred. And even if subsequent soundings should reveal the presence of more or less concentric faults close to the caldera margin, the question of their age would still remain for debate. In a word, though the presence of faults is essential to the theory of collapse, it is not conclusive proof that the caldera was produced solely by engulfment. Obviously, downsinking and insliding of the walls may also follow explosion. It is therefore on the negative evidence already presented that principal reliance must be placed. Fortunately, that evidence is so strong as to admit of little doubt.

# The Age of Crater Lake

Having concluded that the caldera was formed principally by engulfment of the top of Mount Mazama, we are next confronted with the question, How long ago did this take place? Although the answer cannot be exact, it seems worth while to inquire concerning the evidence.

1. Just before the beginning of the culminating eruptions, the glaciers on the south side of the volcano descended to elevations between 6250 and 6500 feet. These glaciers occupied the upper stretches of Munson, Sun, and Kerr valleys and were between 3 and 4 miles long. Where they cross the present rim of Crater Lake they were probably not more than 150 feet thick. Everywhere else on the mountain the ice had retreated above the caldera rim. The Union Peak volcano either was completely bare or at most supported very small patches of ice under the shadow of the summit crags. Yet at the time of their greatest extent, many glaciers in this region were more than 10 miles long and more than 1000 feet thick. Therefore the rigorous climate of the Pleistocene must have ended long before the top of Mount Mazama disappeared.

If the volcanic peak existed today, glaciers would descend almost as low as the present caldera rim. In deep canyons the ice might even descend to still lower levels. In other words, if the top of the volcano were restored, the glaciers would not be very different from those which mantled the upper part of the cone just before its demolition.

2. A second criterion of age, though no more precise, is the degree to which the deposits of pumice and scoria have been entrenched by stream erosion. Since the glowing avalanches choked the canyons around Crater Lake, streams have cut narrow, steep-walled troughs to a maximum depth of 300 feet, to an average depth between 100 and 200 feet, and to a width of approximately 600 feet. In a few places streams have cut through the pumice and scoria to the moraines and lavas below, but thus far they have made little impression on these older deposits. Considering that where the pumice and scoria are massive and columnar they fall easy prey to undermining and that where they are incoherent they are just as readily removed, the small size of the troughs signifies a recent origin. Furthermore, when the caldera was formed the heads of the deepest troughs were still occupied by remnant tongues of ice, and for some time thereafter melt waters must have provided a plentiful source of power. In addition, the gradient of the streams was steep; when erosion began, Annie Creek fell 200 feet per mile, and the gradients of the other streams were not much smaller. If the average rate of downcutting was as little as an inch a year, and in the beginning it must have been very much more, it would have required only 3600 years to carve even the deepest canyon.

3. When the caldera was formed, the Klamath Lakes and Klamath Marsh did not contain much more water than they do today. At most their levels were a few feet higher.

4. The walls of Crater Lake have suffered little erosion considering their steepness and the nature of the rocks involved. All who have witnessed the havoc caused by a single summer storm will agree that imposing slides of talus might well be formed in a few thousand years. Besides, most of the large slides may have been produced when the top of the volcano was engulfed.

5. The recency of the eruptions which brought about the collapse of Mount Mazama is also attested by the fact that pumice covers the youngest moraines on the east flank of the Cascade Range, by the lack of deep weathering of the ejecta, and by the surprisingly regular manner in which the thickness of the pumice varies from place to place. Except along the banks of the major streams, the thickness has scarcely been influenced by denudation.

6. The forests on Mount Mazama, though scantier than they are today, were otherwise similar. Within the limits of the park trees were few, but below 4500 feet they grew in profusion, especially on the western side of the volcano.

Fragments of charcoal collected from the deposits of glowing avalanches in road cuts bordering the Rogue River were examined by R. A. Cockrell, of the Forestry Department, University of California. From cuts along the Diamond Lake highway, a mile or so from the Union Creek junction, charred pieces of the following trees were identified: *Pinus monticola* (western white pine), *P. Lambertiana* (sugar pine), *P. albicaulis* (whitebark pine), *P. contorta Murrayana* (lodgepole pine), *P. ponderosa* (western yellow pine), *Abies concolor* (white fir), and *Pseudotsuga taxifolia* (Douglas fir). From the roadside quarry near McLeod, close to the snout of the Rogue River pumice flow, carbonized limbs of white pine and Douglas fir were identified. In Beaver Marsh, beyond the east base of Mount Mazama, the only tree represented was lodgepole pine.

At all these localities, trees of precisely the same kinds are now thriving on the pumice. The inference is that when the pumice was laid down the climate was almost if not locally quite the same as that of today. To test this inference further, Waldo Glock studied the growth rings of the charcoal logs. His conclusion was that when the trees were living, rainfall came dominantly but not exclusively in the winter, as it does today. Many logs had rings indicating growth under ideal conditions, with a plentiful supply of water; it should be recalled, however, that most of the carbonized trees were growing close to the banks of rivers, where more groundwater was available than elsewhere.

The extensive and detailed studies made by H. P. Hansen, of Oregon State College, of the pollen grains in post-Pleistocene peat bogs of the Pacific Northwest provide another welcome clue to the age of Crater Lake. At four localities, he examined thick sections of peat resting on the pumice blown from Mount Mazama during its culminating eruptions. In three of these profiles, the highest proportions of lodgepole pine were found just after the yellow-pine maximum. Hence, Hansen concludes that the eruptions occurred during or soon after the dry period denoted by the yellow-pine maximum, at a time when the climate was slightly drier than it was soon thereafter and at present. If, as many geologists suppose, the warm, dry third of post-Pleistocene times was between 4000 and 7500 years ago, then on this evidence Crater Lake was formed approximately 5000 years ago.

Only one thick deposit of peat was examined in the immediate vicinity of Crater Lake, namely a 6-foot section in Munson Valley, about a mile below Government Headquarters. Here the peat had accumulated in a marshy basin cut through the pumice deposits left by glowing avalanches. Unfortunately, there is no means of determining how soon after the eruptions the peat began to form. At the bottom of the section, two-thirds of the pollen was from lodgepole pine; 17 per cent was from whitebark pine; the remainder consisted of approximately equal amounts from western yellow pine, mountain hemlock, and ?noble fir. Upward, the content of the three last-named species showed little change, but whitebark pine increased while lodgepole pine diminished, until at the top the former was in excess. This succession either indicates progressive cooling of the climate and increase in precipitation, or may simply imply that lodgepole pine, having fewer soil requirements, was the pioneer invader.[1]

7. What may prove to be an additional clue to the age of Crater Lake has lately been obtained by J. E. Allen[2] from observations in northeast Oregon. Many valleys in that region were deeply filled with alluvium during the warm, dry third of post-Pleistocene time, when the carrying power of the streams was considerably diminished. Subsequently, when the climate became cooler and moister, the rejuvenated streams cut deep channels in their alluviated floors and in their fans and exposed a layer of extremely fine, white pumice not far beneath the surface. Accordingly, the pumice must have fallen toward the close of the driest part of post-Pleistocene time, or approximately 5000 years ago. It must be admitted, however, that until more detailed studies are made, the provenance of the pumice remains in doubt. The thickness, the distribution, and the fineness of the ejecta, as well as the nature of the glass particles, accord well with the view that Mount Mazama was the source; on the other hand, the few samples thus far examined microscopically contain a larger proportion of hornblende rela-

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[1] Much additional information concerning pollen analyses of this and other relevant peat deposits appears in: H. P. Hansen, "Post–Mt. Mazama forest succession on the east slope of the Central Cascades of Oregon," Oregon State Coll. Pubs., Dept. of Botany. In press.

[2] Oral communication.

tive to hypersthene than is usual in the pumice unquestionably erupted by Mazama.

8. A minimum age for Crater Lake is given by the trees on Wizard Island. The oldest of them is said to be approximately 800 years of age, and if, as seems probable, the last eruptions from Wizard Island killed all the pre-existing vegetation, then the final activity took place a little more than 800 years ago. Unfortunately, we cannot tell how long it took for the Wizard Island cone to grow to its present height, nor can we say how long an interval of quiet followed the formation of the caldera before volcanism was renewed.

All the criteria listed above are admittedly vague. Taken together, however, they suggest that Crater Lake is, geologically, of very recent origin. That Mount Mazama was destroyed long after the period of maximum glaciation can no longer be doubted; that the catastrophe happened toward the end of a long dry period and shortly before the present pluvial cycle seems equally certain. Tentatively, the evidence points to an age of approximately 5000 years, and to a maximum of 7000 and a minimum of 4000 years. Yet we may anticipate with confidence that continuing studies of deglaciation in the High Cascades, coupled with examination of the present and former lakes in the lowlands to the east, especially in relation to the pumice deposits and postglacial vegetation, will provide a more accurate solution of this fascinating problem.

# The Relation of Ancient Man to Crater Lake

When Crater Lake was formed, Indians were living on the plateau to the east. Their implements have recently been unearthed beneath deposits of pumice from Mount Mazama.

During the past few years, many test pits have been made on the banks of the Deschutes River, near Wikiup Butte, with the object of selecting a suitable site for a dam (see map, figure 16). In the course of these excavations, several knives of obsidian were found in a layer of glacial outwash covered by 3 to 4 feet of Crater Lake pumice.[1]

Eighty miles east of Crater Lake, near the village of Paisley, Cressman recently excavated a small cave. Here again, beneath a thin stratum of pumice, human artifacts were obtained. Among the remains were part of a mat made of shredded sagebrush bark, some sagebrush rope, a two-ply twisted basketry warp, the butt end of an atlatl point, and chalcedony and obsidian scrapers. Elsewhere,[2] evidence has been published to show that the pumice above the artifacts came from Mount Mazama.

In a second cave near Paisley, Cressman uncovered a rich collection of bones overlain first by a sterile deposit a few feet thick and then by a layer of pumice. Among the bones Chester Stock[3] identified those of bison, mountain sheep, camel (probably *Camelops*), horse, a large dog (wolf), a fox, and probably bear. Among these, writes Stock, "are two genera, namely horse and camel, that we generally regard as more characteristic of the Pleistocene than of the Recent epoch. Some of the remaining forms do not range in the region where the cave is located at the present time." Unfortunately, there is no means of knowing how long a time is represented by the sterile layer separating the bones from the overlying pumice.

Some day, it can hardly be doubted, bones of animals, possibly also bones of man, will be discovered beneath the pumice blown from Mount Mazama, for the glowing avalanches, erupted before the formation of Crater Lake, rushed down the flanks of the volcano at such tremendous speed that everything in their path must have been destroyed. When such remains are discovered, they will most likely be in the valley of the Rogue River. In the meadows bordering the Rogue, hundreds of animals must have been surprised and overwhelmed by the onrushing flows of pumice. By the chance of erosion or excavation their entombed bodies may yet be brought to light.

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[1] L. S. Cressman, "The Wikiup Damsite No. 1 knives," Amer. Antiquity, vol. 3, no. 1, pp. 53–67, 1937.

[2] L. S. Cressman and Howel Williams, "Early man in south central Oregon: evidence from stratified sites," Univ. Oregon Monogr., Studies in Anthropol., No. 3, 1940.

[3] Chester Stock, letter to L. S. Cressman, 1939.

# Post-caldera Eruptions

Most calderas are partly, and some are almost wholly, filled by the products of later eruptions. After a period of quiescence, measurable usually in tens or hundreds of years, magma finds its way upward either through fissures on the caldera floor or through arcuate fractures along the margins. If it escapes along marginal fractures, rim volcanoes are formed, and these may continue to grow until they discharge lavas down the outer flanks of the volcano, as they did in the Medicine Lake caldera of northern California.[1] If, on the other hand, magma escapes from fractures well inside the caldera, the new vents may either show a linear arrangement, as in the calderas of Tengger in Java and Aso in Japan, or they may be scattered without order. Whether the new vents are distributed at random or form a definite pattern depends primarily on the manner in which the collapse of the caldera occurs, and on the shape of the underlying reservoir.

Soundings of Crater Lake have so far failed to reveal evidence of eruption of lava from arcuate fissures at the base of the caldera walls. A lava lake may once have occupied the deepest part of the floor and may account for the surprising flatness of the area enclosed by the 1900-foot isobath. Apart from Wizard Island, however, there are no definitely proved centers of activity on the caldera bottom. Considering the recent origin of Crater Lake in relation to the size of Wizard Island and the age of its last eruptions, the period of quiet following the collapse of Mount Mazama was probably short.

## Wizard Island

Wizard Island (see plate 20) consists of a perfectly symmetrical cinder cone almost completely encircled by dark, rugged flows of lava. The summit of the cone rises 763 feet above the level of the lake, and the area of the cone and lavas exposed above water approximates a square mile. Were it not for the sparse covering of trees, one might suppose that the eruptions had only lately ceased, so fresh is the appearance of both the cone and the flows. Set in the placid blue waters of Crater Lake, the somber island leaves an indelible picture in the mind.

*The cone.* The cone itself is little more than ½ mile in diameter and consists chiefly of black, scoriaceous lapilli and blocks. Near the summit these are mixed with red and brown "cinders." Fine ash is notably scarce. Though most of the fragments measure more than an inch across, there are few large pieces. Near the base of the cone bombs 2 feet in diameter may be found, and on the crater rim there are blocks of lava more than 6 feet in diameter. Well rounded bombs are exceptional. Most of the ejecta are angular or subangular and must have been blown out when practically solid. Some of the fragments were undoubtedly formed by explosive shattering of lava flows and temporary conduit plugs. Eruptions of Strombolian type characterized only the final stages of activity, for near the crater rim there is much agglutinate, indicating that the latest ejecta were still sticky enough when they fell to adhere to adjacent fragments.

Not all the cone consists of fragmental material. During its growth there were several subterminal eruptions of lava. These were scarcely more than an oozing through the sides of the cone.

At the summit there is a bowl-shaped crater, approximately 300 feet across and 90 feet deep (plate 20). On its floor, a patch of black, scoriaceous lava, crowded with foreign inclusions, represents the filling of the central conduit.

*The main lava flows.* After the cone had been built, lava escaped from fissures at the base. Soundings to the east of Wizard Island suggest that flows from this source cover an area of approximately 3 square miles, but whether these hidden lavas were erupted after the building of the cinder cone, or, as seems more probable, form the basement, cannot be determined. The visible post-cinder-cone flows spread chiefly toward the west, in which direction they extend for ½ mile. The tongue of lava projecting into Skell Channel is marked by concentric curved ridges up to 60 feet in height, separated by troughs many of which are occupied by jade-green pools floored with diatomaceous earth. As seen from the Watchman, the wave-like surface of the flow is quite distinct (plate 21, figure 1). The lava composing this western flow is of the block type. As it moved, the surface layers broke into sharp-edged, angular fragments, many more than 10 feet across and some even 30 feet in maximum dimension, with smooth, glassy skins.

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[1] C. A. Anderson, "Volcanoes of the Medicine Lake Highland, California," Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 25, pp. 347–422, 1941.

After the coarse, block lava had been erupted, a second pulse of magma broke through the northwest side of the cone. In this later flow there are no large blocks; indeed, few measure more than 3 feet across. It is also much more scoriaceous and weathers to brown crusts. In general, the boundary between the two flows is sharp. Locally, the front of the younger one forms a steep wall as much as 40 feet in height; elsewhere, well defined tongues of the finer, scoriaceous lava poured down channels in the earlier blocky flow (plate 21, figure 2). In other places, however, the flows merge in a broad intervening zone. Hence, they may represent a continuous emission of magma increasingly rich in gas.

On the east side of Wizard Island, lavas form only a narrow strip, rising between 20 and 200 feet above the lake. Here they support a thicker growth of vegetation and have weathered to a thin soil. Judged by these features, they may be older than the lavas on the opposite side of the island.

Not all the flows of Wizard Island issued from a single vent. Those on the east escaped from radial fissures, as is suggested by the presence of lava ridges above the general level. On the southwest slope of the cone the principal vent lies about 300 feet above the lake, but doubtless other vents are buried beneath slides of scoria. Only by assuming a number of source fissures is it possible to account for the form and distribution of the flows.

Mention should be made, in conclusion, of an interesting feature to be seen through the water of the lake in the bays on the southwest side of the island. Here, the lake floor is pitted by many deep cavities, more or less lined with diatomaceous earth. Several measure 3 or 4 feet in diameter and are roughly cylindrical; others are irregular and much larger. Considerable doubt attaches to their origin. Some observers maintain that they may be related to fumarolic activity. More probably, the cylindrical pits represent molds of tree trunks that were enclosed by lava, and the larger depressions are cavities between blocks on the surface of the flow.

*Age of Wizard Island.* Considering the perfect symmetry of the cone, the well preserved form of the crater, and the freshness of the lava surfaces, the eruptions seem to date back only a few centuries. But if we assume that the oldest trees on the island began to grow only after the eruptions had ceased, then, according to H. H. Waesche, activity must have ended approximately 800 years ago. These were the last eruptions in the Crater Lake region. If fresh magma still exists beneath Wizard Island, it must be at considerable depth, for there are now no signs of solfataras, mofettes, or hot springs in the vicinity. It would be rash to assert, however, that Mount Mazama is quite extinct.

# The Glaciation of Mount Mazama

The geologist who visits Crater Lake cannot fail to see at once abundant signs of glaciation on every side. If he approaches from the south, his attention is drawn during the last 2 miles of the journey to the fresh moraines through which the road makes its tortuous way. Arriving at the crater rim, he soon finds striated pavements of lava on the very brink of the cliffs (see plate 22, figure 1), and as his eye follows the rim to the southeast he sees two spectacular U-shaped notches, one at the head of Kerr Valley and the other at the head of Sun Valley. These are obviously cross sections of deep glacial troughs. If then he turns toward the western wall of the caldera, he is prepared to guess that the great lava flow of Llao Rock occupies yet another glacial valley, for its base has the unmistakable form of a river channel modified by the passage of ice.

Such are the most obvious indications of glaciation on Mount Mazama. Closer inspection shows not only that glaciers once spread far beyond the limits of the park, but that they must have existed on the flanks of the growing cone at an early stage, for glacial moraines are interbedded with the oldest lavas on the caldera walls. The building of Mazama took place almost entirely during Pleistocene time, and throughout much of its history the cone was covered by ice.

It is of course impossible to unravel the stages of advance and retreat of the earlier glaciers, since their deposits can only be seen in cross section on the caldera walls. All that can be said is that from time to time, both in response to climatic changes and as a result of volcanic activity, the glaciers were partly or wholly destroyed and then readvanced.

## EVIDENCES OF EARLY GLACIATION ON THE CALDERA WALLS

It was Atwood[1] who first discovered that many glacial layers occur on the walls of the caldera, and that the surfaces of some of the oldest lavas have been striated by passing ice. Since then, many more horizons of glacial debris have been found and ice-polished surfaces have been discovered a few feet from the edge of the lake. The general distribution of these glacial deposits is shown on the map, figure 31, and in the panoramas, plates 23 to 29.

Those who may wish to examine these evidences of glaciation will find the best and most convenient exposures along the north wall between Pumice Point and the Wineglass, and along the east wall immediately south of the V-shaped lava flow on Redcloud Cliff. On the west and south walls of the caldera the glacial deposits are not so well developed, and access to most of them is rather hazardous.

The following notes refer to the principal evidences of glacial action on the caldera walls. For an artist's reconstruction of the appearance of Mount Mazama at the time of its maximum glaciation, see plate 22, figure 2.

### *Cloudcap Bay*

There is no better place to examine the alternation of lavas with glacial moraines than in the cliffs bordering Cloudcap Bay (plates 10 and 23). A short distance south of the center of the bay, coarse bouldery till and fluvioglacial gravels underlie the lowest lava flow and probably extend beneath the level of the lake. These are the oldest visible glacial deposits on Mount Mazama. When they were laid down, the volcano cannot have been more than 9000 feet high. Probably the records of earlier glaciers lie beneath the waters of Crater Lake. The thickness of the exposed deposits varies between approximately 20 and 30 feet. Resting upon them is a flow of andesite of about the same thickness, the top of which is well polished and striated. Above this flow rests a second layer of till approximately 25 feet thick, and above this a second lava flow 10 to 15 feet in thickness (plate 10). This is succeeded by a third deposit of till, about 50 feet thick, capped in turn by a third flow up to 80 feet in thickness. The upper surface of this third lava is extremely rough and shows no trace of glacial action. But above it there lies a poorly exposed layer of coarse bouldery detritus which is more likely of glacial than of pyroclastic origin. If so, then within a vertical distance of some 250 feet from the water's edge there are four glacial layers separated by three lava flows, vivid testimony to the advance and retreat of glaciers on the side of the young volcano.

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[1] W. W. Atwood, Jr., "The glacial history of an extinct volcano, Crater Lake National Park," Jour. Geol., vol. 43, pp. 142–168, 1935.

Above this alternating series of flows and tills follow ten or twelve thin sheets of andesite, on the topmost of which may be found a fifth lens of glacial material with a maximum thickness of 15 feet. This is overlain by the pink and buff pumice in which the spectacular Cottage Rock has been cut, and by the thick dacite flow from Cloudcap. On top of the latter lies a patchy deposit of bouldery till, then a layer of coarse lump pumice, and finally another till, part of the sheet which occurs almost everywhere along the caldera rim. In all, then, there are seven glacial horizons on the caldera wall at this point. None of these layers, with the exception of the highest, can be traced continuously for more than a few hundred yards. As might be expected, most of them are lenticular deposits left by narrow valley glaciers.

How quickly most of the glacial layers pinch and disappear laterally is well seen by comparing the cliff section on the north side of Cloudcap Bay with that on the south side, just described. On the north side only the topmost till and one other of the six exposed to the south can be identified with certainty, though a third layer may also be present as indicated on the panorama, plate 23. The lowest till can be traced intermittently as far as Skell Head. Occasional striae indicate the direction of ice movement to have been south 20° west, almost parallel to the shore of the lake. On the top of the small promontory north of Skell Head, 30 feet above the lake, the till rests on a striated floor of lava, the striae trending south 65° west. A quarter of a mile north of Skell Head, the till descends to the water's edge and disappears.

### *The Northeast Wall, from Grotto Cove to Cleetwood Cove*

The thin flows which form the "primary slope" of Mount Mazama disappear beneath the water near the Wineglass (plate 24) and reappear near Palisade Point, about 2 miles away. It is precisely in this stretch that the thickest glacial accumulations of any on the caldera walls are to be found.

Large glaciers descended the northeast side of Mount Mazama for a long time after the outpouring of the thin flows of andesite. In so doing, they carved a broad and deep valley, and subsequently filled it with morainic mounds and fluvioglacial outwash. Not until several hundreds of feet of such deposits had been laid down did lavas again pour down this side of the volcano.

Owing to slides of pumice and lava from the cliffs above, exposures of glacial material are sporadic and small. Nevertheless, almost the entire wall below the lava cliffs of Grotto Cove, Roundtop, and the Palisades probably consists of glacial debris.

Close to the shore of Grotto Cove, south of the Wineglass, there are many small exposures of bouldery till and finely bedded glacial sands and gravels. Particularly interesting are the rounded glacial boulders embedded in the margins of the dike which traverses the caldera wall in this vicinity. But it is beneath the Roundtop flow that the most spectacular exposures are to be seen. Here, as the photograph, plate 25, shows, the base of the Roundtop flow has the form of a broad W. The explanation is not difficult to find, for wherever the bottom of the lava is exposed it rests on coarse morainic debris. At one place, near the western edge of the flow, the underlying till is exposed to a thickness of 6 feet and many striated boulders are completely embedded in the lava. Both here and in the other smaller exposures beneath the flow, the moraine has been deeply reddened by gas action. Apparently the Roundtop lava flowed down a shallow valley littered with hummocky glacial mounds.

After the flow had solidified, glaciers again advanced down this side of the volcano. The crust of the lava was polished and striated, and patches of bouldery till were left scattered on the surface. Once more the ice retreated. Showers of pumice and then deposits of welded tuff were laid down over the Roundtop flow and the Wineglass. For the last time, the ice readvanced, leaving irregular patches of till on top of the welded tuff. Before the culminating pumice explosions and prior to the formation of the caldera, the ice had once more suffered a retreat, leaving this part of the volcano bare.

Adjoining the Roundtop lava on the northwest is a second thick sheet of andesite which likewise poured down a broad valley cut in glacial deposits. Accordingly, the thickest part of the flow is in the center, where the great cliffs of jointed lava descend to the lake forming the so-called Palisades. Where there is no talus, the underlying materials consist chiefly of fluvioglacial sands and gravels. Especially clear are the exposures beneath the eastern "wing" of the flow, where the downward succession is as follows: talus, 10 feet; coarse, bouldery till, 10 feet; fine glacial sands and gravel, 4 feet; coarse till with boulders up to 2 feet across, 6 feet; fine, well bedded sand with scattered boulders, 20 feet; coarse till with boulders up to 3 feet across, 5 feet; fine, well bedded sand and gravel, 12 feet; till with boulders up to 18 inches across, 5 feet. Toward Roundtop, these bedded deposits probably double or even treble in thickness and interfinger with the more massive moraines already described.

Beneath the western "wing" of the Palisade flow, the underlying rocks are almost wholly hidden by talus, and where they do outcrop their nature is such that it is impossible to decide whether they are glacial in origin or represent the bouldery products of volcanic mudflows (lahars). Similarly, no certain glacial deposits have been identified beneath the dacite flow in Cleetwood Cove.

Although, as we have noted, the top of the Roundtop flow has been polished by ice and lenses of glacial till rest on it, no such signs of glaciation can be seen on the bristling top of the Palisades flow, above which lie first a thick pile of coarse lump pumice and then welded tuff. Above the tuff, however, are bouldery deposits that seem to represent glacial moraines. The Cleetwood flow is also overlain in part by lump pumice, and, along its lower margins, by welded tuff. The higher, central part of the flow, on the other hand, is overlain by bouldery detritus up to 150 feet thick. Whether this deposit is entirely morainic or the product of eruptions which hurled out occasional glacial boulders cannot be decided. Ice did, however, cover at least part of the Cleetwood flow, for in the cuts along the Rim Road the lava is overlain first by red, buff, and white lump pumice, then by glacial sands and bouldery till, and finally by the ash and pumice deposits laid down during the culminating explosions of Mount Mazama.

### *Cleetwood Cove to Pumice Point*

Throughout this stretch of the caldera wall, as the panorama, plate 26, shows, an irregular layer of glacial debris occurs at or close to the base. About midway along the stretch, the glacial deposits rest on a scratched surface of lava only 20 feet above the lake.

Higher up the caldera wall, there are other lenses of till interbedded with flows of andesite and sheets of dacite pumice, but their presence is indicated only by scattered erratics in the talus.

On Pumice Point itself, three distinct glacial beds have been recognized. These are restricted to the upper half of the caldera wall (plate 11, figure 1). Separating the pumice deposits from the main series of lavas below is a glacial layer approximately 7 feet thick, composed of bouldery till overlain by glacial sands. The lava surface on which they rest is marked by striations trending south 25° west. Above the glacial deposits follow 47 feet of incoherent lump pumice and then a second layer of glacial sand, 5 feet 6 inches thick. This glacial layer cannot be traced continuously, but a short distance away, on the same horizon, a bed of bouldery till, 10 feet thick, may be seen resting on the glaciated surface of a thick lava flow intercalated in the pumice. At this point the striations trend south 18° west. Above the till, Atwood uncovered a dark soil band containing much charred vegetation. Obviously, the eruptions of Mount Mazama were interrupted long enough for plants to gain a foothold on the till before being destroyed by the next explosions. Eruptions then continued until approximately 130 to 170 feet of bedded pumice accumulated on the old soil. Thereafter the glaciers readvanced, leaving in their wake a third and nonpersistent bouldery till up to 6 feet in thickness. Finally, after the ice had once more retreated, the concluding pumice eruptions began. The evidence for this history is presented in the section, figure 8.

### *Steel Bay*

Few parts of the caldera wall are more difficult of access than the cliffs overlooking Steel Bay, and much hazardous climbing will be required before the details of this section are determined. Enough is known, however, to say that in addition to the till which occurs almost everywhere just beneath the products of

Mazama's last explosions, there are at least two other glacial horizons. Their approximate positions are illustrated in the panoramic sketch, plate 28. The lower layer rests on the hummocky tops of the lavas whose dike feeders are exposed near the base of the caldera walls. It is not a continuous band, but a series of lenses composed partly of till and partly of well stratified fluvioglacial sands, from which water seeps at many places. Higher up the walls are thin flows of andesite, patches of pink pumice, and blocky explosion debris, associated with much morainic material. At one locality my assistant, Roy Turner, found a well striated pavement; at another we found a small cave at the base of a lava flow, and on the cave floor several glacial boulders. Many erratics also occur in the talus hereabouts.

### *Llao Rock*

Most geologists who see Crater Lake decide even from a distance that the dacite flow of Llao Rock occupies a glacial valley. That this is actually the case may be verified by closer study, for an almost continuous layer of morainic debris occurs immediately beneath the western "wing" of the flow, thoroughly reddened by gas action and containing many striated boulders up to 18 inches across. Toward the margin of the flow, the till is considerably admixed with and overlain by dacite pumice. Above the pumice lies a younger till which partly overlies the edge of the Llao flow (plate 12, figure 2). Clearly, the eruption of the Llao dacite was both preceded and followed by glaciation. What seem to be the same two layers of till are well exposed on the spur about 150 yards south of the western edge of the Llao flows (plate 30, figure 1). At least two other layers underlie the western "wing" of the flow, as shown in the panorama, plate 29, and beneath one of them there is a well striated surface of andesite.[2]

The glacial till immediately below the western "wing" of Llao Rock can be followed almost to the bottom of the old pre-Llao valley, but there it is obliterated by the feeding pipe of the flow. On the opposite, eastern slope of the old valley there is no trace of glacial material.

Although no moraines have been found immediately below the eastern "wing" of Llao Rock, two thin bands of fluvioglacial sand, separated by a flow of andesite, are exposed at the base of the great deposit of pumice which underlies the dacite, approximately at the same elevation as the bottom of the pre-Llao valley (plate 29).

### *West Wall of the Caldera, from Llao Rock to Eagle Cove*

The oldest glacial deposit in this part of the walls lies a short distance south of the Devil's Backbone, approximately 300 feet above the lake (panorama, plate 29). The eye accustomed to the particular shade of gray that most of the tills exhibit has no difficulty in distinguishing it even from afar. When Atwood first discovered the occurrence, he noted glacial striae trending north 65° west on the underlying lava, but these are no longer visible.

On the west and southwest sides of the caldera, the topmost till is absent only on the highest points of the rim, such as Hillman Peak and the Watchman. Presumably these eminences were never covered by ice. Beneath this youngest till there are many beautifully striated surfaces of lava. In the col between the Watchman and Discovery Point, approximately due west from the top of Wizard Island, A. E. Long discovered the partly carbonized stump of a tree in the position of growth at the contact of the till with the overlying pumice. Across the top, the stump measured 13½ inches; across the bottom, 15½ inches; its length was 52 inches. The lowest 8 inches of the stump had not been carbonized, but the rest had been burned by the hot pumice. The discovery is important not only because it proves that vegetation existed at this elevation on the volcano just before the destruction of the summit, but also since it implies that a long period of quiescence preceded the last, catastrophic explosions.

A short distance south of this locality, the youngest till is both underlain and overlain by dacite pumice. Generally, however, the till rests directly on the striated surface of a thick flow of andesite, which lies in turn on a second layer of till. Below this is a second thick flow of lava. Then follows a conspicuous layer of pink pumice, and finally a third lens of till, between 50 and 60 feet thick, approximately 500 feet above the lake. The wall below is entirely made up of thin sheets of andesite.

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[2] W. W. Atwood, Jr., *op. cit.*, p. 155, fig. 16.

Near Discovery Point, one may stand on the polished surface of the topmost lava and look down 40 feet to the striated crust of an older lava overlain by 10 feet of till. At Glacier Point, about 1½ miles to the south, a succession of three tills, each overlying striated lava, may be seen within 150 feet of the caldera rim. These occurrences have already been described and illustrated by Atwood.[3]

Space precludes a detailed discussion, but it may be noted that at several other places on the west and southwest walls of the caldera many lenses of glacial till occur within a few hundred feet of the rim. An excellent section is exposed just inside the rim, about 150 yards south of the Devil's Backbone. Here, beneath the youngest till and its overburden of pumice, lie older deposits of pumice up to 30 feet in thickness, and beneath these a band of coarse, bouldery till no less than 120 feet thick, which rests on a striated surface of andesite. From the sandier layers in the till, water oozes continually.

The youngest till reaches its greatest development in the saddle between the Lake Trail and Crater Lake Lodge. It may be seen to advantage from the parapet of the Sinnott Memorial. The morainic deposits here reach a thickness of more than 120 feet. Worthy of particular note is the fact that there is no cover of pumice. This moraine is in fact a relic of the Munson glacier, which at the time of the destruction of Mount Mazama still extended as far south as the Government Headquarters, 1½ miles beyond the rim of the caldera.

### *South Wall of the Caldera, from Eagle Cove to Kerr Notch*

On the great face of the Eagle Crags, not a single layer of till can be found interbedded with the lavas, the only moraines being those between the highest flows and the overlying, youngest pumice deposits of Mount Mazama. Glaciated pavements close to Dyar Rock, at an elevation of more than 7800 feet, suggest that when these moraines were laid down the entire ridge separating Sun from Munson Valley, and perhaps even the tops of Garfield and Applegate peaks, were buried under a continuous sheet of ice. The Sun Valley glacier was then continuous over most if not all of Dutton Ridge, and united in a single gigantic field of ice with the Kerr Valley glacier. This must have been the time of maximum glaciation. It was then that the great U-shaped Sun and Kerr valleys were chiefly cut. Long afterward, when the glaciers had not only disappeared from the tops of Vidae and Dutton ridges, but retreated up Sun and Kerr valleys above the present rim of the caldera, dacite pumice explosions laid down between 20 and 50 feet of ejecta in the bottoms of Sun and Kerr notches. The ice then readvanced and buried the pumice with moraines. Except near the margins, these final moraines either are entirely bare or are covered only by the merest sprinkle of pumice. It therefore seems likely that when the last pumice eruptions took place glaciers still occupied the bottoms of Sun and Kerr notches. Such pumice as does occur on the surface of the last moraines may represent vestiges of thick piles that fell onto the ice, or ejecta washed into place at some later date.

The oldest record of glaciation in this section of the caldera wall appears between half and two-thirds of the way down the face of Dutton Cliff, immediately above the top of the Phantom cone (page 30 and plate 6).

### *Danger Bay and Sentinel Rock*

We have now practically completed the circuit of the caldera. Between Kerr Notch and Cloudcap Bay, glacial deposits are confined to the upper part of the walls. On the shoulder to the east of Kerr Notch, between two-thirds and three-quarters of the distance up the walls, are two distinct layers of bouldery till, each about 80 feet thick, separated by a flow of andesite. In the upper till there are lenses of well cemented fluvioglacial sand and gravel, pebbles of which may be found embedded in the bottom of the overlying lava. A third till rests on the topmost lava and beneath the youngest pumice deposits of Mount Mazama. This is part of the ubiquitous sheet of till just inside the caldera rim.

On the north side of Danger Bay, the walls display a pronounced unconformity, an upper group of lavas and pyroclastic rocks resting in a broad and shallow basin pitching toward the lake and cut in a lower volcanic series. Copious springs gush from the contact and lush vegetation flourishes there. It was thought at first that some of the upper lavas might have issued from Mount Scott, for this would readily explain their lakeward dip. Closer study shows, however, that this is not the case. On the contrary, the upper lavas seem to have filled a glacial valley (plate 30, figure 2). This alone would fail to account for their inward dip, since the slope of the underlying lavas is in the opposite direction. The answer is to be found in the presence of glacial till on the old valley bottom. Near the lake the till is thin, but higher up the caldera wall and farther from the lake it thickens rapidly. Presumably a terminal moraine occupies the valley a short distance behind the caldera wall, and it was against the inner face of this moraine that the younger lavas accumulated. Nowadays, water percolating through the jointed lavas finds its way down the face of the moraine and so empties into the lake.

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[3] *Ibid.*, pp. 150–152, figs. 10–12.

After the glacial valley had been filled, a new vent opened beneath Sentinel Rock and a thick flow of andesite was erupted from it. The glaciers then readvanced, overriding the flow and leaving on its surface an irregular deposit of till (plate 14, figure 2). This may be seen conveniently on the trail from the Rim Road to the top of Sentinel Point. On the trail itself, the Sentinel lava is overlain by 50 feet of till, though a short distance to the north and south the layer dwindles to a few feet in thickness and disappears west of Cloudcap. There is no hint of a corresponding till above the Redcloud dacite. Above the till, on the Sentinel Point trail, is a layer of lump pumice 42 feet thick, then a block layer of about the same thickness, and finally 50 feet of finer lump pumice, products of the last explosions of the volcano. The same three layers can be seen on Point Reflection above the till, and in the opposite direction they can be seen arching over the top of the Redcloud dacite (plates 10 and 23) and continuing over the lavas of Skell Head.

### Direction of Glacial Striae on the Caldera Walls

Had Mount Mazama been a perfectly symmetrical cone, all the glacial striae on the caldera rim would be radial with respect to the former summit. That such is far from being the case is plainly seen from the map, figure 31. Atwood supposed that the striae point not to a single center of dispersal, but to two, one approximately above the center of the lake and the other above Wizard Island. He therefore suggested that toward the end of its growth the main cone bore on its western flank a parasitic cone, "Little Mazama," just as Shasta bears on its western side the parasitic Shastina, and he thought that Wizard Island might have been built by renewed eruptions through the same conduit which had supplied the lavas of this hypothetical "Little Mazama." Certainly if "Little Mazama" ever existed it would have served as a second center of ice dispersal, and its presence would account for the trends of the striae on the western rim of the caldera. The trends of the striae can be explained satisfactorily, however, without recourse to such a hypothesis, for Hillman Peak, now bisected by the rim, must have acted as a "cleaver," splitting and deflecting the glaciers which swept down from the main peak of Mazama.

The most noteworthy departure from the general radial arrangement of the striae left by the last glaciers of Mount Mazama is to be found along the northeast rim, between Roundtop and Skell Head. On Roundtop, the striae run almost north and south; on Skell Head they are directed toward a point far to the east of the center of the lake. Nothing in the present topography can account for these aberrant trends, and it can only be surmised that the glaciers on the northeast slope of the main volcano were deflected from their radial course by parasitic cones.

The striae on the lavas lower down the caldera walls are too few to permit definite conclusions regarding the directions taken by the earlier glaciers on the volcano. It may be mere coincidence that most of the older striae on the west and north walls of the caldera trend toward a point about halfway between the center of the lake and the summit of Wizard Island. Certainly it would be rash to conclude that when these striae were formed the top of Mount Mazama lay in that position. Along the east wall of the caldera, the older striae run approximately parallel to the lake shore; they are much more nearly tangential than radial in direction. Possibly when they were produced the glaciers on the east slope of Mazama were deflected by others from the opposing slopes of Mount Scott. Even in its infancy, as we have seen, Mount Mazama was a complex of overlapping cones built by shifting or multiple vents, and it is therefore not surprising that the glacial striae fail to show a regular pattern.

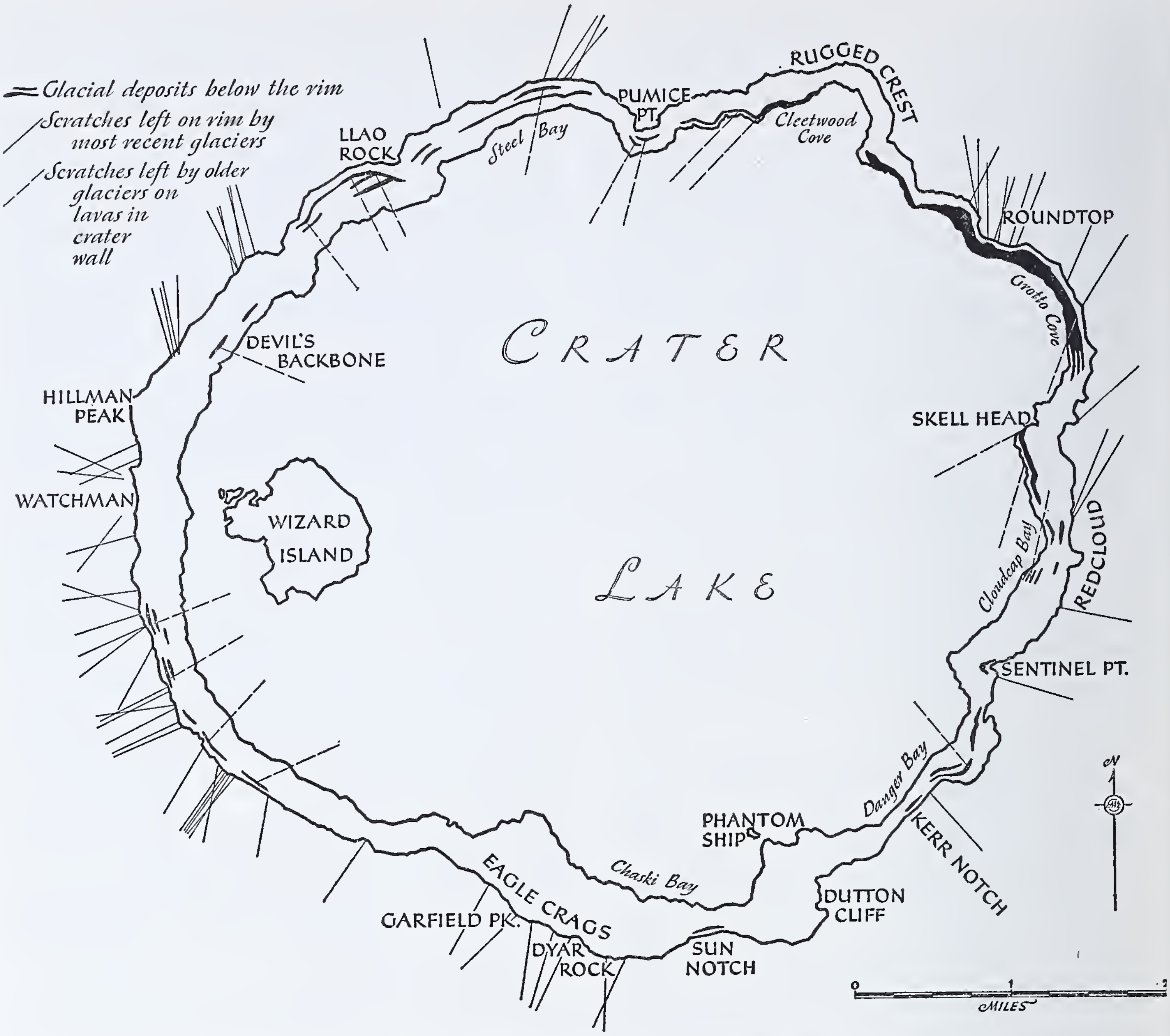

Fig. 31. Glacial striae and deposits on the rim and walls of Crater Lake. Topmost tills on and close to the rim are omitted. (Compiled by W. W. Atwood, Jr., Loren Miller, Roy Turner, and Howel Williams.)

## Summary of Glacial Evidences on the Caldera Walls

The walls of Crater Lake reveal a complex history of alternating volcanism and glaciation. Doubtless many other High Cascade volcanoes passed through a similar history. Only here is the record laid bare for inspection.

The record at Mount Mazama shows that even the oldest of the exposed lavas are interbedded with glacial debris and that this debris must have been deposited before the volcano was more than 9000 feet high. Glaciers may have existed on the volcano long before this. Until the main andesitic cone had almost reached its maximum height, the glaciers were small and either had little power to erode or were periodically destroyed by falls of ash and flows of lava before they had time to carve deep valleys. That is why none of the older glacial deposits on the caldera walls, with the exception of one on the walls of Danger Bay, lie in U-shaped troughs, but are regularly interbedded with the volcanic rocks. Only when the andesitic eruptions had almost come to an end and the dacites on the south slope of the volcano had been erupted did the maximum glaciation begin. Not until then were the great glacial valleys carved on the sides of the cone. At that time, Mount Mazama must have been all but completely mantled by ice, and long glacial tongues extended far beyond the limits of the park. After these extensive glaciers had dwindled and were confined to the upper part of the volcano, the dacites of Llao Rock, Grouse Hill, Cleetwood Cove, and Redcloud were erupted from the Northern Arc of Vents. Though the low margins of these flows were later covered by ice, the higher parts were never glaciated.

Glaciation seems to have begun later on the south side of the volcano than elsewhere, and the moraines on that side are therefore almost confined to the top few hundred feet of the walls. Yet when the period of maximum glaciation began it was on this same side of the volcano that the largest glacial canyons were carved. On the north, east, and west walls of the caldera we look in vain for U-shaped valleys comparable with the Munson, Sun, and Kerr valleys on the south. We can only infer that it was some peculiarity in the configuration of the lost, upper part of Mount Mazama which caused the largest of the glaciers to develop on the sunward-facing slopes.

## EVIDENCES OF GLACIATION OUTSIDE THE CALDERA

The records of glaciation on the outer slopes of Mount Mazama are widespread. During the stage of maximum glaciation, ice covered all save the highest pinnacles on the divides. These were the only bare spots on an otherwise uninterrupted field of ice.

On the south and east sides of the volcano, the glaciers swept down to the base and deployed onto the flats beyond. Some of them must have been 10 miles long and ended at elevations as low as 4500 feet. On the north side, the glaciers were probably no less extensive and were confluent with those of Mounts Thielsen and Bailey. The longest glaciers, however, were those which flowed down the canyons of Castle, Copeland, and National creeks until they united in a single stream of ice in the valley of the Rogue. The snout of this composite glacier was near Union Creek Ranger Station, at an elevation of about 3400 feet. On this side of Mount Mazama, therefore, the ice spread approximately 17 miles from the summit. During this period of maximum glaciation, glaciers also covered the Union Peak volcano, and some of them served to augment the tongues of ice from Mount Mazama.

### *The Munson Valley or Annie Creek Glacier*

One of the largest glaciers on Mount Mazama, and certainly the last to survive, passed over the caldera rim near Crater Lake Lodge, continued down Munson Valley, and entered the broad canyon of Annie Creek. At the time of maximum glaciation, it was united with the Sun Creek glacier to the east, and all but a few points on Vidae Ridge were covered by ice. Where the snout of the Munson–Annie Creek glacier lay at the time of its greatest extent cannot be determined with precision, though probably it was at least 3 miles south of the park boundary and not far above Fort Klamath.

Inside the park, Annie Creek has cut through the pumice in many places. For 7 miles up the valley, as far as Government Headquarters, recessional moraines are exposed at intervals on the canyon floor. Wherever they appear, there are copious seepages on the canyon walls.

One of the finest lateral moraines anywhere within the park may be seen on the north wall of Annie Creek canyon a short distance inside the south boundary. For more than a mile it runs parallel to the creek as an imposing embankment, from 100 to 150 feet high. The crest stands between 500 and 600 feet above the bottom of the creek, which thereabouts coincides closely with the base of the pumice fill. How much deeper the "bedrock lavas" lie we have no means of determining, but probably not more than a few tens of feet. Accordingly, when this lateral moraine was laid down, the Annie Creek glacier, even 9 miles from the top of Mount Mazama, was approximately 500 feet thick.

Continuing up Annie Creek, the next exposures of till occur about 100 yards below the Main Falls. The river has here penetrated some 6 feet of morainic debris. A mile to the east, between 250 and 300 feet above the canyon bottom, till may be seen resting on the bench which marks the contact between the lavas of the Union Peak volcano and the dacites of Mount Mazama.

Half a mile above the falls, and from there to the confluence of Annie Creek with its East Fork, the west bank shows several striated surfaces of lava overlain by coarse piles of morainic material. Northward to Munson Valley, irregular mounds of till appear at intervals at the base of the walls of both Annie Creek and its Middle Fork, and the streams repeatedly pour in small cascades over a bouldery bottom, as if for most of their course they had already cut through the overburden of pumice and were flowing on the surface of moraines. Where Pole Bridge Creek tumbles into Annie Creek it has likewise stripped off the cover of pumice, and one may walk over morainic debris from the rim of the canyon to its base.

If the reader consults the topographic map of Crater Lake National Park published by the U. S. Geological Survey, he will observe that on the divide between Annie Creek and its Middle Fork the contours are unusually sinuous. As Atwood first discovered, this irregularity is the expression of a buried kame-and-kettle topography. In other words, the surficial deposits of pumice are mantled on hummocky moraines. That this is so may easily be verified by study of the neighboring walls of the Middle Fork, where the upper and drier slopes of pumice pass down into wet banks of bouldery till.

From this point northward to Government Headquarters, the moraines are covered by only a thin sheet of pumice, and many rise above the pumice as conspicuous ridges. Even the pumice is greatly admixed with glacial debris. In the upper part of the valley the proportion of pumice gradually diminishes. From Government Headquarters to the caldera rim, the moraines stand bare and their forms seem scarcely to have been modified by erosion. These are the youngest moraines of Mount Mazama. Because they are free from even the thinnest veneer of pumice, they must have been deposited after the great explosions which led to the collapse of Mount Mazama and the formation of Crater Lake. In other words, when this catastrophe took place, the Munson Valley glacier still reached as far down as Government Headquarters, and the collapse of the top of the volcano cut off the glacier between a mile and a mile and a half above its snout.

Unlike the glaciers that flowed down Sun and Kerr valleys, the Munson Valley glacier did not excavate a deep notch in the rim. Nevertheless, if the thick moraines near the Sinnott Memorial were removed, a shallow valley half a mile wide would mark its channel.

### *The Sun Creek Glacier*

The canyon of Sun Creek is the most imposing glacial trough on the slopes of Mount Mazama. Where it is truncated by the rim of the caldera it has a perfect U-shaped section (plate 31). Its floor is approximately ¼ mile across, and the tops of the opposing cliffs are ¾ mile apart.

At the time of maximum glaciation, ice spread across Vidae Ridge, and the Annie Creek and Sun Creek glaciers were continuous. Similarly the divide between Sun Creek and Kerr Valley—Dutton and Grayback ridges—was then concealed. Evidence for this is to be seen in the presence of bouldery drift covering the slopes south of Dutton Cliff. Even the top of 6122 Hill on Grayback Ridge is plastered with drift. Therefore, the ice in Sun Creek canyon, opposite the hill, must once have been approximately 1000 feet thick.

In the lower part of Sun Creek canyon, the traces of the former glacier are almost completely buried by thick deposits of pumice. But about a mile inside the south boundary of the park, on the west wall of the canyon, a well defined bench, approximately 60 feet above the bottom, marks the contact between the pumice and the underlying moraines. Exposures of drift are few and poor, but the presence of marshy ground and the abundance of glacial boulders are ample proof of the existence of recessional moraines.

At an elevation of 5900 feet, the walls of Sun Creek canyon consist principally of glacial drift, considerably reworked and mixed with pumice. This hybrid deposit continues upstream for a mile, at which point the floor of the valley is interrupted by cliffs of lava. From the top of these to the rim of the caldera, 1½ miles higher, the valley is covered with hummocky moraines. At lower elevations these are veneered with pumice, but upward the sprinkle of pumice gradually disappears until in the last ½ mile the moraines are bare. Presumably, therefore, the Sun Creek glacier was still in existence, though a small relic, when the final eruptions began. The ice, which had once been almost 1000 feet thick as it passed through Sun Notch, was then no more than 100 or 200 feet thick.

### *The Kerr Valley Glacier*

The lowest point on the rim of Crater Lake is at Kerr Notch, familiar to all visitors on account of its beautifully symmetrical U shape. At this point the caldera wall is only 550 feet high. Once, the notch was filled to the brim with a glacier that continued beyond for perhaps 8 miles, but when the last pumice eruptions took place the glacier had been reduced to a thickness of little more than 100 feet, and its snout lay only about a mile beyond the caldera rim.

The traces left by the Kerr Valley glacier at the time of its greatest extent are almost wholly concealed, but the presence of drift on the top of 6605 Hill, on the east side of Sand Creek, indicates that 3 miles beyond the caldera rim the ice was at least 600 feet thick. A mile to the northwest of this locality, on the south slope of Anderson Bluffs, an imposing lateral moraine is still preserved. At lower elevations, Sand and Wheeler creeks have yet to cut through the overburden of pumice to the drift below.

### *Glaciers of Mount Scott*

The presence of glacial striae on the caldera rim at Sentinel Rock and west of Cloudcap, and of morainic mounds beneath pumice on the summit of Anderson Bluffs, shows that the glaciers of Mount Mazama once swept round the southern base of Mount Scott. This parasitic cone formed another center of ice dispersal. Down the east slopes of the cone two glaciers, between 4 and 5 miles long, followed the canyon of Scott Creek and the unnamed canyon to the north, as far as the basalt plateau. The cluster of dacite domes at the east base of Mount Scott was formed after these glaciers had retreated. But even after the glaciers had shrunk until they no longer covered the present east rim of the caldera, ice lingered in the cool recesses of the cirque on the northwest side of Mount Scott. At the mouth of this small cirque and on its southwest side one may still see well preserved moraines. If a glacier remained in the cirque when the great pumice explosions took place, it can have been no more than a few hundred yards long.

### *The Bear Creek Glacier*

A powerful glacier formerly poured northeastward across the caldera rim near Cloudcap, entered the valley of Bear Creek, and flowed down it to the plateau beyond. As it retreated within the present boundaries of the park, it left behind two huge lateral moraines about a mile apart. Of these, the southern is the most imposing in the park. It rises 250 feet above the valley floor, and is heavily charged with boulders, some of them 10 feet across.

Up to Cascade Spring, the source of Bear Creek, the floor of the valley is blanketed with lump pumice. The spring itself issues from the base of a bouldery moraine resting on lava. Still higher up the valley, the hummocky drift is only lightly covered with fine granular pumice.

### *Glaciers on the North Slope of Mazama*

Prior to the eruption of the Roundtop and Palisade lavas, as we have seen, large glaciers occupied the northeast slope of Mount Mazama for a long time. Even after the eruption of these lavas, ice again covered what is now the northeast rim of the caldera. The extent of these older glaciers is a matter for conjecture, for the heavy deposits of pumice on this side of the volcano effectually hide all evidence.

By the time the dacites of Cleetwood Cove and Grouse Hill were extruded, the glaciers on the north slope of Mount Mazama had been reduced to thin tongues only a few miles long. The absence of drift on the lower slopes of Timber Crater shows that this basaltic cone was also built after the period of maximum glaciation.

At their greatest extent the glaciers on the north slope of Mount Mazama were confluent with those from Mounts Bailey and Thielsen. A great field of ice then existed about the headwaters of the Rogue River and in the basin south of Diamond Lake. On the northern slopes of those two volcanoes the glaciers descended to approximately 4000 feet, to Toolbox Meadows and the upper part of Mowich Park, where copious streams issue from the terminal moraines to feed the North Umpqua River. The Desert Ridge volcano was the source of smaller glaciers tributary to those from Mount Mazama. The whole northwest corner of the park, even the top of Crescent Ridge, was then under ice, all of which found its way into the Rogue River glacier, to be united with the glaciers that flowed down the western slopes of Mount Mazama.

### *Glaciers on the West Slope of Mazama*

The entire western rim of the caldera, with the exception of the summits of Hillman Peak and Llao Rock, shows the marks of passing ice. Moreover, glaciers continued to cross what is now the caldera rim until a very late stage, for most of the top of the Watchman lava flow, one of the youngest andesites of Mazama, is striated.

Except in the canyons of Copeland and Bybee creeks, the drift on the western slopes is covered only by a thin and patchy cover of pumice. Few well defined moraines occur on these slopes; instead, hummocky mounds of coarse drift rise from flats littered with gravelly and sandy outwash.

At the head of Copeland Creek, the river tumbles in a series of cascades, 125 feet high, over the end of a recessional moraine in which boulders up to 15 feet across may be found, and for a mile below, the pumice is considerably mixed with glacial debris. A similar recessional moraine is exposed beneath pumice on the tributary of Bybee Creek where it is cut by the meridian 122° 15′ west.

At the time of maximum glaciation, ice filled the canyons of both Copeland and Bybee creeks as far down as their confluence with the Rogue River.

### *The Castle Creek Glacier*

The ice on the southwest slope of Mount Mazama entered the broad and deep canyon of Castle Creek and there joined the ice discharged from the north slope of Union Peak. In point of size, this was the largest of all the glaciers fed by Mount Mazama, for its total length was approximately 17 miles. Not only did it fill the canyon of Castle Creek, but it covered the entire ridge to the north with the exception of the topmost 100 feet or so of the cinder cone forming 6236 Hill. Even 5 miles west of the park boundary, the lava ridge on the north side of the canyon was under ice.

### *The Rogue River Glacier*

All the glaciers on the northwest, west, and southwest slopes of Mount Mazama ultimately united in a single glacier that flowed down the valley of the Rogue. From its source down to the confluence with Union Creek, tributary valleys entering from the east fed the main glacier with ice. Whether or not the Rogue River glacier was also fed from the west is uncertain, but it seems probable that such glaciers as existed among the ridges of the Western Cascades were confined to the summit regions and never extended as far down as the principal valleys.

It would be interesting to know just how far down the valley of the Rogue the ice extended, but the evidence has been removed by erosion or is buried by pumice. Perhaps the snout of the glacier never extended farther down than Union Creek Ranger Station, that is, below 3400 feet.

In the Cascade Range farther north, as Thayer has shown,[4] the Pleistocene glaciers were much more extensive. Indeed, the earliest glaciers descended the North Santiam River valley to an elevation of approximately 700 feet, traversing two-thirds of the width of the Western Cascades, and even the late Wisconsin ice reached as low as 2000 feet.

### *The Union Peak Glaciers*

The sides of the Union Peak volcano have suffered much more from glacial erosion than those of the younger Mount Mazama. Probably the volcano was already extinct before the onset of the main glaciation, and when the ice was at its greatest extent, the entire cone was covered. The direction of ice flow is shown on the map, figure 23. On the north and east sides, the glaciers fed the Castle and Annie Creek glaciers respectively; those on the south emptied into the great U-shaped canyon of Red Blanket Creek.

Since the col just south of Castle Point is covered with drift, the glaciers on the northwest side of the volcano were thereabouts 650 feet thick. Erratics from the summit tuff cone were carried down to Pumice Flat by the same glaciers that left the moraines bordering Pole Bridge Creek, near the Klamath Falls highway. A mile or so south of this locality, where the ice left Pumice Flat to join the Annie Creek glacier, a fine curved moraine is still preserved. Another and much larger arcuate moraine occupies the depression followed by the old road which leaves the Medford highway just west of Annie Spring, though this seems to have been built by the joint action of ice from the Union Peak volcano and Mount Mazama.

The highest moraines on Union Peak, in the cirque heads at the base of the summit pinnacle, are covered with a light sprinkle of pumice. Therefore, when the catastrophic destruction of Mount Mazama took place the glaciers of Union Peak either had disappeared altogether or were reduced to tongues measuring at most a few hundred yards in length.

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[4] T. P. Thayer, "Geology of the Salem Hills and the North Santiam River Basin, Oregon," Oregon State Dept. of Geology and Mineral Industries, Bull. 15, 1939.

# Changes of Water Level in Crater Lake

Presumably Crater Lake began to develop immediately after the formation of the caldera, and at first the water was probably strongly acid on account of the condensation of fumarolic vapors rising through cracks in the floor. Subsequent deepening of the lake was caused partly by direct precipitation of snow and rain and partly by short streams and springs discharging from the walls. Hence, the water is now of exceptional purity. In general, the drainage is outward from the caldera, following the dip of the lavas and interbedded pyroclastic rocks. At several points, however, particularly where lavas rest on glacial debris, the drainage is reversed and enters the lake. Noteworthy examples may be seen on the walls south of Sentinel Point, on Dutton Cliff, and under the topmost flows overlooking Grotto Cove. At these and similar places, copious springs discharge down the caldera walls and often the vegetation near them is unusually lush.

How rapidly the lake level rose there is no means of telling, nor can it be said at what stage the cone of Wizard Island first appeared above the surface. Considering that the submerged walls of the caldera are probably composed in the main of lava flows and that the more porous pyroclastic layers tend to increase in abundance upward, the lake level presumably rose most rapidly during the early stages.

Several years ago, Gordon Hegeness, then on the ranger-naturalist staff, discovered diatomaceous earth on Wizard Island, approximately 50 feet above the surface of the lake. Though there are no corresponding benches on the caldera walls, the occurrence may be considered adequate proof of a former high stand of the water.

During the past forty years, the level of the lake has fallen approximately 13 feet, leaving a series of benches along the shore. According to Diller, there is in addition a seasonal oscillation of about 4 feet, the level being highest early in May when the snows are melting fast, and lowest at the close of the summer. Undoubtedly many springs on the outer slopes of the volcano derive part of their supply from the lake, but it would require long and careful study to determine even approximately how much escapes in this manner. When Diller studied the lake, he estimated that the level during the summer sank 0.0155 foot per day, notwithstanding a small influx, and that the loss by evaporation accounted for 0.0125 foot per day. The remaining fall, 0.003 foot per day, must have been caused by percolation. During the past few years, the amount added to the lake by precipitation and inflow has approximately balanced the loss by evaporation and percolation.

# Microscopic Petrography

## LAVAS OF THE UNION PEAK VOLCANO

All who have worked among the lavas of the High Cascades have been faced with the troublesome problem of deciding upon a distinction between andesite and basalt. All agree that the crowning cones of the Cascade Range, Mounts Shasta, Mazama, Hood, Rainier, Baker, and Adams, to mention a few, are composed principally of hypersthene andesite. But these cones, huge as they are, form only a small fraction of the total volume of lava in the High Cascades. Certainly the dominant lavas of the range are more basic. Some, for example the intracanyon flows (the Santiam, Umpqua, Rogue River, and Butte Creek lavas), are unmistakable olivine basalts, but many more lie so close to the boundary between basalt and andesite that their proper position can only be established by chemical analysis. Among these problematic rocks must be included most of the pre-Mazama lavas within Crater Lake National Park, and most of those which form the High Cascades southward to Mount Shasta.

Thayer,[1] working among the lavas of the north-central Cascades in Oregon, found it convenient to consider all the olivine-bearing lavas basalts. If olivine is regarded as a diagnostic mineral, then certainly all the lavas of Union Peak and virtually all the High Cascade lavas that stretch southward to Shasta are basalts. Many authors prefer to regard the nature of the plagioclase as diagnostic, and include among the basalts those lavas in which the average of the total feldspar is more basic than $Ab_1An_1$. The difficulty here, however, is that the porphyritic feldspar is strongly zoned in an oscillatory fashion and much of the microlithic feldspar is too minute for accurate determination. To distinguish between andesite and basalt on the basis of the plagioclase would therefore be an interminable task at best, and in the case of glass-rich flows it might be quite misleading. The only satisfactory solution of the matter is, of course, to prepare as many chemical analyses as possible. Of the four analyses made from the rocks of the Union Peak volcano, one has a silica percentage of 54.38; in the others the percentages are 55.63, 56.75, and 56.95 (see analyses 4, 5, 6, and 7; references here and below are to tables on pages 148–152). Bearing in mind the ratio of lime to alkalis, most geologists would hesitate to classify the three more siliceous rocks as basalt, even though they do contain a small amount of olivine. It is therefore suggested that they be called olivine-bearing basaltic andesites. Such rocks are probably the main lavas on Union Peak, Mount Thielsen, and Mount Bailey, and are more voluminous than true olivine basalts in the High Cascades to the south. In the opposite direction, however, the principal pre-Mazama lavas of the High Cascades are, as Thayer has demonstrated, olivine basalts with a silica percentage of less than 55.

### *Lavas of the Main Cone*

The typical flows of the Union Peak volcano are generally distinguishable from the lavas of Mount Mazama by the presence of small phenocrysts of olivine and by the paucity of porphyritic feldspar. Pyroxene is invariably present in large amount, the hypersthene normally in the form of euhedral or subhedral prisms of early growth, and the augite[2] in the form of irregular grains in the groundmass. Texturally the flows vary widely, from intergranular to ophitic and hyalopilitic. There is no systematic variation in the relative proportions of olivine and hypersthene according to texture, for olivine may be just as plentiful in the coarse, ophitic flows as in the dense, fluidal types. Nevertheless, there is often a reciprocal relation between the two minerals, irrespective of texture.

A common feature of the Union Peak lavas is the partial or complete replacement of olivine by granular magnetite or hematite or both. Usually this change is confined to the rims of the olivine. Alteration to serpentine is exceptional. In some instances, replacement of olivine by iron ores took place at an early stage, for shells of fresh augite surround the altered crystals. In other instances, the change may have been brought about at a late stage, for it affects olivine and augite alike in those lavas which have been most deeply reddened by gas action.

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[1] T. P. Thayer, "Petrology of later Tertiary and Quaternary rocks of the north-central Cascade Mountains in Oregon," Bull. Geol. Soc. Amer., vol. 48, pp. 1611–1652, 1937.

[2] In the petrographic notes that follow, no attempt has been made to distinguish between varieties of monoclinic pyroxene, though pigeonite is realized to be abundant. For a discussion of the mineralogy of Cascade lavas, see: Richard Bogue and E. T. Hodge, "Cascade andesites of Oregon," Amer. Mineralogist, vol. 25, pp. 627–665, 1940.

If porphyritic feldspar is present, it is invariably corroded and marked by intense zoning, and in general the composition ranges from basic labradorite inside to oligoclase or acid andesine at the rim. Occasionally the cores of the phenocrysts may be composed of acid bytownite. The microlithic feldspar, on the other hand, is predominantly medium to acid andesine.

Two typical specimens were selected for analysis. The one from Red Blanket Canyon (analysis 5) has the texture described and figured by Patton as "fluidal interstitial." A little black glass is present, but essentially the rock is composed of closely packed, subparallel microliths of acid labradorite, intergranular augite and ore, and a light sprinkling (3 per cent) of porphyritic olivine, partly altered to serpentine. The other specimen analyzed (no. 4) is an extremely fine-grained lava with the following content: microporphyritic olivine, 5 per cent, almost entirely replaced by magnetite; rare phenocrysts of hypersthene and augite, 2 per cent; stumpy, zoned phenocrysts of acid bytownite–acid labradorite, 25 per cent; and a dense, intergranular base of microlithic andesine, anhedral augite, and ore.

Finally, it should be noted that few of the Union Peak lavas are devoid of minute quantities of either tridymite or cristobalite, the former occurring usually in triangular interspaces in the groundmass, and the latter on the walls of vesicles.

### *Intrusions near Bald Top*

At the southeast base of Bald Top, the Union Peak lavas are intruded by irregular dikes, parts of which are pale buff or gray, and the bulk dark green, weathering to a deep-brown crust. Compared with the surrounding lavas, these dikes are much coarser in grain and are typified by their ophitic texture. Essentially, they consist of olivine crystals up to 2 mm. in length, intergrown with zoned labradorite. Augite, though forming occasional large ophitic plates, is far subordinate to olivine, and hypersthene is even less abundant.

But the most distinctive feature of the dikes is the difference in the degree of alteration of the pale and dark parts. The dark-green parts owe their color to widespread change of the olivine to antigorite and bowlingite, and to the presence, in triangular interspaces, of yellowish-green chlorophaeite. This wholesale serpentinization of the olivine is all the more striking in view of the rarity of such alteration in the adjacent lavas.

Here and there the dark-green, serpentinized rocks are cut by branching joints, bordering which the lava is distinctly paler. Seen in the field, the pale lava appears as "veins" 2 to 3 inches wide, sharply delimited from the dark-green rocks on either side by thin bands stained with limonite. The textures and primary minerals in the light and dark types are identical. But contrary to expectation, for one might suppose alteration to be most advanced along joints, the pale lava is perfectly fresh and contains no chlorophaeite.

To this apparent anomaly, Fuller's studies elsewhere[3] provide a clue. According to his interpretation, the pale rocks bordering the joints remained fresh because of the escape of volatiles, and this accounts also for their more open, diktytaxitic texture. Farther from the joints which served as avenues of escape for volatiles, the rocks suffered autometamorphism, chiefly hydration, though the feldspars were not affected. What the significance of the limonite-stained bands separating the fresh from the hydrated rocks may be, is not understood.

### *The Micronorite Plug of the Union Peak Volcano*

The summit tuff cone of the Union Peak volcano is intruded by a large, vertical-sided plug, similar to the Minto plugs described by Thayer[4] and to the plugs of the Mount Thielsen and Howlock Mountain volcanoes.[5] The summit pinnacles of several other Cascade cones are of the same kind.

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[3] R. E. Fuller, "Deuteric alteration controlled by the jointing of lavas," Amer. Jour. Sci., ser. 5, vol. 35, pp. 161–171, 1938.

[4] T. P. Thayer, *op. cit.*, pp. 1628–1631.

[5] Howel Williams, "Mount Thielsen, a dissected Cascade volcano," Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 23, pp. 195–214, 1933.

The dominant rock of the Union Peak plug is a pale-gray, minutely porous micronorite cut by broadly spaced joints. The grain size is fairly uniform and the texture is pseudo-lamprophyric to ophitic. Slender laths of feldspar are crossed haphazard by thin prisms of hypersthene, and are partly enclosed or separated by augite. The feldspar laths are zoned from labradorite in the center to albite along the rims. Discrete crystals of albite may also be found in the fine base and lining cavities. Olivine is present only in minor amount, but euhedral grains of magnetite are abundant. No feature of these rocks is more distinctive, however, than the unusual development of silica minerals. In parts of the plug, the joint faces are "frosted" with myriads of tiny plates of tridymite, and the dense matrix is composed largely of fan-shaped twins of this mineral. Cristobalite is also widespread. Some of it occurs in the groundmass, where it may have developed from glass under the influence of mineralizers, as suggested by Larsen;[6] but by far the bulk occurs in the form of spheroids, up to 1 mm. in diameter, on the walls of cavities. Dutton,[7] who first detected them, observed that sanidine and euhedral augite are associated with them on the cavity walls. Equally characteristic is the association of both tridymite and cristobalite with abundant, well formed crystals of hematite. There can be no doubt that both the silica minerals and the hematite are a product of fumarolic gases. That they are far more plentiful in the plug than in any of the extruded lavas is only to be expected, for hot gases must have continued to rise up the central conduit for a long time.

Associated with the pale-gray rocks just described are darker, denser, less vesicular, and more closely jointed rocks which seem to have been intruded later. In these, the feldspars show a larger range in size. Moreover, the augite is no longer related ophitically to the feldspar, as in the coarse, pale facies, but is entirely intergranular. The hypersthene-augite ratio is extremely variable, though the former always predominates and is generally three to five times as plentiful as the latter. Commonly augite forms jackets enclosing the hypersthene prisms. In some specimens, brown glass may form as much as 10 per cent of the volume.

In the coarse parts of the Minto plugs, Thayer found olivine to be rare, and he suggested that resorption during slow cooling might account for the fact. In the Union Peak plug, on the contrary, there is no systematic relation between the coarseness of the rocks and the amount of olivine. Indeed, the mineral is least common and most altered in the fine-grained rocks. The content of cristobalite, tridymite, and hematite does, however, vary almost directly with the coarseness. The open-textured, coarser rocks afforded easier passage to the fumarolic vapors responsible for those minerals.

## PRE-MAZAMA LAVAS IN THE NORTHWEST CORNER OF THE PARK

The lavas just described do not differ essentially from those which outcrop beyond the northwest base of Mount Mazama, and those related to Bald Crater and Red and Desert cones. All these flows are characterized by the presence of porphyritic olivine. In many, tridymite is developed in the dense groundmass and granules of cristobalite may be found lining vesicles. They vary principally in the character of the groundmass, as Patton has set forth in detail. Only two analyses are available, one of a lava from the base of Red Cone and the other from the ridge north of Desert Cone (nos. 9 and 8). The former is the most basic rock in the park and is an unmistakable basalt; the other contains 58.65 per cent of silica and, like the dominant lavas of Union Peak, is best referred to as an olivine-bearing basaltic andesite. Between these two types there are all gradations.

Examples of hypersthene-free, olivine-rich basalt have been recognized southeast of Bald Crater. They may also be found on and around the bases of Desert and Red cones. Essentially, the hypersthene-free flows consist of porphyritic crystals of olivine (5 to 8 per cent), many of which are partly or wholly replaced by magnetite or hematite or both, accompanied by occasional phenocrysts of basic labradorite, in a fluidal groundmass composed of subparallel microliths of medium labradorite, intergranular augite, and ore.

[6] E. S. Larsen, "Petrologic results of a study of the minerals from the Tertiary volcanic rocks of the San Juan region, Colorado," Amer. Mineralogist, vol. 21, pp. 687–694, 1936.

[7] C. Dutton, "Cristobalite at Crater Lake, Oregon," Amer. Mineralogist, vol. 22, pp. 804–806, 1937. In my report on the Thielsen and Howlock plugs, the tridymite and cristobalite were mistakenly identified as zeolites.

In some specimens, the vesicles are lined with opal, and a little tridymite may be detected in the groundmass. Patton noted that some cavities in the lavas at the east base of Red Cone are also lined with apatite and pseudobrookite.

Associated with the flows just enumerated are others in which the content of porphyritic feldspar is so much higher that they resemble some of the dark andesites of Mount Mazama. Patton referred to these as "andesitic basalts." Examples are common on Desert and Crescent ridges. Some are intergranular, some hyalopilitic. The feldspar phenocrysts are invariably embayed, charged with glass inclusions, and strongly zoned. The cores of some are at least as basic as acid bytownite, though the rims may be andesine. Commonly they include grains of augite and ore. Olivine, partly altered to iddingsite, is also present.

An unusual type of lava comes from the crest of 6789 Ridge, a spur running eastward from Desert Ridge. This is a dense, pale-gray lava with a pseudolamprophyric habit, consisting of a crisscross felt of zoned labradorite laths and prismatic hypersthene, porphyritic olivine, accessory augite and ore, and abundant interstitial tridymite (8 per cent). Hypersthene makes up no less than 15 per cent of the volume, and is approximately ten times as common as augite. The rock resembles much of the coarser facies of the Union Peak plug, and it may not be far removed from the original conduit of the Desert Ridge volcano.

Taken as a whole, the lavas of the Desert Ridge volcano carry more hypersthene than any of the other pre-Mazama rocks; on the other hand, the flows adjacent to Bald Crater and Red and Desert cones tend to be richest in olivine.

Finally, it may be pointed out that whereas basic inclusions are plentiful among the lavas of Mount Mazama, they are scarce among the earlier flows. Sporadic clots of coarse olivine-hypersthene gabbro occur in the lavas of Desert Ridge, but elsewhere inclusions are extremely rare.

### Andesites of Mounts Mazama and Scott

The bulk of Mount Mazama and the whole of Mount Scott are composed of hypersthene andesites. Since they do not differ materially from the andesites already described from the Lassen region, from Mount Shasta, and from Mount Rainier, and since Patton has presented a detailed account of their principal variations, extended notice is unnecessary. As might be expected, they vary widely in texture, from holocrystalline and subophitic to extremely glassy, the dominant types being pilotaxitic. Few are devoid of large phenocrysts of feldspar, and by this criterion alone they are usually distinguishable from the pre-Mazama flows. Besides, olivine, which is almost ubiquitous among the older flows, is an unusual accessory among the hypersthene andesites of Mazama itself. Among the more acid andesites, rare crystals of hornblende make their appearance. Biotite andesites are unknown.

As compared with the pre-Mazama flows and those erupted from parasitic cinder cones, the Mazama andesites are rarely vesicular. They are further typified by many basic inclusions. Indeed, locally these may be so plentiful as to constitute a quarter of the total volume.

Whether the lavas are holocrystalline or hyalopilitic, they have the following characteristics in common: Phenocrysts of plagioclase usually make up between a quarter and half the bulk. Almost without exception, they show pronounced oscillatory zoning, the normal range in composition being from basic labradorite to basic andesine. Occasionally cores of bytownite are present. Ferromagnesian phenocrysts are subordinate both in size and in abundance; in some flows their total content may reach 10 per cent, but generally the percentage falls below 5. Exceptionally, porphyritic augite exceeds hypersthene in amount. Typically, however, hypersthene is twice or three times as plentiful, and in a few flows it is the only ferromagnesian phenocryst. Olivine is absent from most of the lavas and even where present rarely exceeds 1 per cent by volume. Though usually fresh, it may be altered to green serpentine, iddingsite, or a mixture of granular ore and hematite. Where hornblende is developed, it has the strong pleochroism from pale yellow to deep brown and the dark rims of ore characteristic of hornblendes found among andesites in general.

Though the porphyritic constituents of the Mazama andesites differ relatively little in variety and proportion, the groundmass exhibits a wide range of textures. On this basis alone, Patton has already presented a detailed classification. In the pilotaxitic andesites, the matrix consists of slender microliths of oligoclase or acid andesine or both, and irregular grains of augite and ore, set in a mesostasis of crypto- to microgranular material, of uncertain composition but presumably composed mainly of acid feldspar and a little quartz. Hypersthene is rarely present in the groundmass; hornblende and olivine, never. Tridymite, on the contrary, is almost a constant accessory and may constitute more than 5 per cent of the total volume. Cristobalite may occasionally be seen in the groundmass and on the walls of vesicles, though it is far less widespread than in the pre-Mazama andesites.

Some thin flows and the basal parts of a few thick flows are distinguished from the dominant pilotaxitic lavas by the presence of abundant brown glass. To this they owe their darker color. Their texture varies from hyalopilitic to vitrophyric.

Mention should be made in conclusion of some exceptional types of andesite. On the lower, western slopes of the volcano, the normal hypersthene andesites give way to dark and generally vesicular flows either exactly or almost identical with the pre-Mazama lavas already described. In brief, these are hyalopilitic basaltic andesites characterized by a greater proportion of porphyritic olivine than the normal lavas of Mazama, and by the presence of considerable cristobalite. Similar basaltic andesites may be seen at the south end of Sun Meadows. Some of these olivine-bearing lavas are interbedded with hypersthene andesite, but most are products of late eruptions. In view of their similarity to the pre-Mazama lavas, little reliance should be placed on the contacts indicated on the map, plate 3.

Equal difficulty was experienced in the attempt to determine whether some of the paler, more vesicular and glassy, well banded lavas should be classed as andesite or dacite. In default of chemical analyses, the decisions based on field appearance and on microscopic examination can only be tentative. The problematical lavas are as follows: among those grouped with the dacites are the flows on the flanks of Cloudcap and those of Scott Bluffs; among those mapped as andesites are (1) the highly vesicular, tridymite-rich lavas on the crest of Munson Ridge, above Government Headquarters, (2) the crumbly, white, almost pumiceous, tridymite-rich lavas which in many places border the Rim Road where it sweeps across Vidae Ridge, and (3) the finely laminated, cristobalite-bearing, glassy lavas on the west side of Sand Creek valley, near the Lost Creek Ranger Station. Other "dacitic andesites" are listed by Patton.

The dacitic andesites just mentioned, and the basaltic andesites referred to in the preceding paragraph, though widely distributed, constitute only a very small fraction of the total products of Mount Mazama. It should be borne in mind, moreover, that almost all of them were erupted during the later history of the volcano, immediately prior to the eruptions of dacite from the Northern Arc of Vents and the formation of the parasitic cinder cones. The earlier and main activity of Mount Mazama was marked by eruption of little but normal hypersthene andesite.

### *Basic Inclusions in the Andesites*

In the Lassen region, basic inclusions (autoliths) are particularly abundant in the dacites and rare among the andesites. On Mount Mazama, the reverse holds true. These inclusions vary from a fraction of an inch to more than a foot in maximum dimension, the majority measuring 2 to 6 inches across. The larger ones are well defined and stand out distinctly as ovoid nodules; the smallest, seen only with a hand lens or microscope, have irregular outlines and merge indefinitely into the enclosing lava.

The texture of these inclusions is diktytaxitic. Were it not that all contain an interstitial residue of glass, their texture would be described as lamprophyric. Their mineral content is surprisingly uniform. Essentially, they consist of a crisscross felt of slender plagioclase laths and equally slender prisms of hypersthene and augite, together with granular ore, between which lies a matrix composed partly of brown glass and partly of cristobalite or tridymite or both.

Some typical samples may be selected for description. In the Palisades andesite, the inclusions are abnormally abundant and have the following content: zoned laths of andesine–basic labradorite, 70 per cent; acicular prisms of hypersthene and augite, commonly in parallel growth and approximately equal amounts, 15 per cent; granular ore, 5 per cent; pale-brown glass, 2 per cent; cristobalite, 8 per cent. In the enclosing andesite, cristobalite is either rare or absent, though fan-shaped twins of tridymite are widespread.

In the adjacent andesite of Roundtop, the inclusions consist of the same minerals in slightly different proportions. Cristobalite is again plentiful, making up between 5 and 10 per cent of an average sample, though it is rare in the lava itself. Inclusions in other flows show a similar concentration of cristobalite. For instance, in the third flow from the lake edge on Redcloud Cliff, one inclusion has 25 per cent cristobalite though the mineral could not be detected in the surrounding andesite. Still more striking are the relations between the dacitic andesite on Vidae Ridge, 2 miles south of Garfield Peak, and the inclusions within it. In the lava, vesicles and cracks are so plentifully lined with tridymite that the mineral constitutes approximately 10 per cent of the rock. Yet the percentage composition of one of the inclusions is roughly as follows: labradorite, 65 per cent; hypersthene, 10 per cent; augite, 5 per cent; granular ore, 5 per cent; pale-brown biotite, green hornblende, and olivine, each less than 1 per cent; brown glass, 2 per cent; tridymite, 1 per cent; cristobalite, 10 per cent.

Where cristobalite is rare or absent, its place is taken by tridymite. Beautiful examples of tridymite-rich inclusions, in which the fans reach 0.5 mm. in length, occur in the topmost andesite on Sentinel Point and in the thick flow near the caldera rim east of the Wineglass. Whether tridymite or cristobalite is present, the silica was already concentrated in the inclusions before they were incorporated in the surrounding lava. Presumably the inclusions represent partly or wholly crystallized fragments torn from the walls of the conduit by rising lava. This opinion accords with the observation that conduit fillings and dikes on other Cascade volcanoes are characterized by unusual richness in the silica minerals. Hornblende-rich inclusions, like those in the dacites of the Lassen region, have not been seen among the andesites of Mount Mazama, and even among the dacites they are far subordinate to the pyroxenic varieties just described.

In addition to the cognate nodules, there are occasional xenoliths of older lavas, but these, being unaltered, show no peculiarities worthy of special description.

### *Andesites of the Hillman Vent*

The conduit of the Hillman cone is mainly occupied by vesicular, pale-gray, pilotaxitic pyroxene andesite. Not only is this andesite more coarsely crystalline than most of the surface flows, but it is characterized further by paucity of hypersthene. In many places, cavities are lined with cristobalite; elsewhere cracks in the andesite are lined with specular hematite, deposited by fumarolic vapors rising through the conduit.

Along the western, lower edge of the Hillman vent, there are finer-grained and more fluidal andesites characterized by an unusual abundance of hornblende. No lava in the park contains this mineral in greater proportion. Many of the crystals are 2 mm. long. Though some retain a green color, and an extinction angle, Z to c, of 10°, most of them have the yellow to deep-brown pleochroism and small extinction angle of oxyhornblende, and many are partly or wholly replaced by magnetite. In an average sample, the content of hornblende is 5 per cent. Next in importance among the dark phenocrysts is augite (4 per cent). Porphyritic hypersthene is again subordinate (1 per cent). These minerals lie in a pilotaxitic base.

### *Andesites of the Phantom Vent and Cone*

The material composing the plug of the Phantom vent is mainly a gray-green, vesicular pyroxene andesite. Darker, less vesicular andesites cut the paler lava in almost vertical bands. The microscope shows that the difference between these two types is merely one of texture. Whereas in the paler lava the groundmass is pilotaxitic, in the darker lava it is hyalopilitic. In both types, zoned and corroded phenocrysts of andesine-labradorite are plentiful. Porphyritic augite is invariably subordinate to hypersthene, and olivine is only a minor accessory. Most of the olivine and hypersthene has been altered to greenish serpentine and talc; the augite, on the other hand, is only occasionally altered. In some sections, relic grains of quartz, possibly xenocrysts, are present. Tridymite occurs sparingly. Finally, in the more vesicular lavas there is an abundance of waxy, olive-green chlorophaeite.

Flows of similar, slightly altered pyroxene andesite form the greater part of the Phantom cone. Interbedded with them are thick deposits of tuff breccia. These are well exposed on Phantom Ship and the adjacent headland. Characteristically, the pyroclastic rocks consist of greenish, angular fragments up to 2 feet in diameter, set in a paler grayish-green amygdaloidal matrix. Obviously, these rocks have been subjected to widespread hydrothermal action. None of the original ferromagnesian minerals remain. The irresolvable brownish-green substance replacing them is presumably serpentine, possibly accompanied by chlorite. Despite these alterations, both the porphyritic and the microlithic feldspars are unchanged.

The alterations noted above are more pronounced in the angular fragments than in the enclosing tuff, and account for their darker-green color. Presumably, therefore, the fragments were derived by explosive shattering of lavas that had already suffered propylitization. Hydrothermal activity continued after the eruptions and was perhaps responsible for the cavernous weathering of the tuffs. It was at this time that the well formed crystals of quartz and calcite were deposited in the geodes and veins.

Many dikes cut the tuff breccias on Phantom Ship. The interior of most of these intrusions consists of relatively fresh, pilotaxitic hypersthene andesite, but the margins have been deeply bleached by late solutions. The pyroxenes are entirely replaced by serpentine (?bowlingite) and quartz, though the feldspar is fresh. Blotches of "limonite" and veins of hematite cut the rocks haphazard. In the interior of the dikes, on the contrary, the hypersthene and augite are either wholly unaltered or at most but slightly changed to serpentine.

### *Alterations of the Mazama Andesites*

Where fumaroles, solfataras, and hot springs were active, the Mazama andesites have been variously decomposed. In such places, the rocks assume rich orange, yellow, brown, red, and greenish tints. Alteration is especially marked near the vents of the Phantom and Hillman cones, but is also conspicuous at many horizons on the Eagle Crags. Signs of alteration beyond the rim of the caldera are rare.

A common effect of decomposition was to convert the ferromagnesian minerals to serpentine, and to a lesser degree to chlorite and talc. A second effect was to deposit quartz and calcite in open cavities. Where solfataric action was intense, the lavas were converted to masses of milky opal and kaolin, like those so extensively developed around the hot springs of the Lassen region. Here and there chalcedony occurs. Specular hematite and limonite are also characteristic of the solfatarized rocks. Pyrite is surprisingly rare, and pyrrhotite has been detected at only one locality, on the walls of Chaski Bay. The presence of alunite has not been confirmed. Cristobalite and tridymite, as sublimates of fumarolic vapors, are widespread.

## The Southern Dacite Flows and Domes

The oldest dacites of Mount Mazama form the Vidae and Grayback ridges south of Tututni and Maklaks passes, respectively. Patton has discussed them under the title "Sun Creek flow," noting that in general they are more lithoidal and have suffered more devitrification than the dacites erupted from the Northern Arc of Vents.

In general the dacites erupted as flows are much more strongly banded and less pumiceous than those which form the domes. All, however, have the following features in common: (1) abundant zoned phenocrysts of plagioclase, commonly corroded and rich in glass inclusions (10 to 20 per cent); (2) accessory and smaller phenocrysts of pyroxene, hypersthene usually predominating (1 to 5 per cent); (3) abundant tridymite. In many specimens, tridymite flakes are so plentiful that the rocks glisten like frost. Cristobalite, which is almost ubiquitous among the basalts and basaltic andesites of the Crater Lake region, has not been detected among these southern dacites.

Among the phenocrysts, quartz, mica, and orthoclase appear to be absent, and porphyritic oxyhornblende is extremely rare. Much of the porphyritic plagioclase shows intense oscillatory zoning, the general change being from labradorite in the center to oligoclase at the margins. To judge by the strong dispersion and small optic angle, some of the oligoclase may be rich in potash. The porphyritic hypersthene and augite not uncommonly show a peripheral separation of magnetite and hematite, and their normal greenish color gives way marginally to shades of reddish brown.

Glass may formerly have been plentiful in the groundmass of these rocks, for perlitic fractures are common. Now, however, it is generally absent or present only in insignificant amount. It may be that devitrification was accelerated by the action of hot siliceous vapors, since the coarsest felsitic intergrowths occur along cracks in which tridymite is most plentiful. In other samples, ovoid areas of clear microfelsite are scattered in a matrix of pale-brown cryptofelsite, and the margins of the ovoid spots may be accentuated by a concentration of "limonitic" pigment. In still other lavas, streams of microlithic oligoclase and acid andesine so far predominate over the interstitial microfelsite that the groundmass takes on a trachytic aspect. Spherulitic dacites have been recognized only among the flows; they seem to be lacking from the pumiceous, white dacites of the domes.

Only one specimen of the lavas in question has been analyzed (no. 24). This came from the cliffs on the east wall of Sun Creek approximately ½ mile south of Maklaks Pass, and is typical of the flows in that vicinity. Though the silica content is 71.32 per cent, the ratio of lime to alkalis and the presence of abundant tridymite suggest that the rock should be classified, not as rhyolite, but as tridymite-rich pyroxene rhyodacite. Its affinities with the quartz latites are obviously close. Possibly some of the finely banded lavas northwest of Lost Creek Ranger Station, which are shown on the map as andesites, are in reality dacites, though it would require chemical analysis to verify the suggestion.

## THE YOUNGER DACITE FLOWS

The lavas discussed under this caption are those erupted as domes and flows from the Northern Arc of Vents, namely, those of Llao Rock, Grouse Hill, Cleetwood Cove, and Redcloud Cliff. With these are included the lavas of Cloudcap and Scott Bluffs.

Among the features that serve to distinguish the dacites of the Northern Arc of Vents from the older southern dacites, the chief is the fact that the glass of the younger lavas is rarely devitrified. A second distinction is the much greater development, especially at the tops and bottoms of the flows, of black obsidian. Thirdly, pale-gray pumiceous types of lava are more plentiful among the older dacites. Fourthly, the dacites of the Northern Arc are in general much poorer in tridymite. And finally, though they are never rich in hornblende, few are entirely without this mineral. Many of the lavas of Cloudcap and Scott Bluffs, on the other hand, closely resemble the southern dacites, and some are hardly to be distinguished from acid andesites.

### *The Llao Dacite*

The great sheet of lava forming Llao Rock is mainly composed of black obsidian, which is locally spherulitic, and partly of pale-gray, more vesicular and lithoidal dacite. Commonly the dense obsidian is streaked with highly pumiceous layers. Basic inclusions are comparatively rare. Patton has already given a lengthy description of the Llao dacite, and since the principal varieties are almost identical with those of the dacite dikes beneath Llao Rock, of which an account may be found on page 143, a few words must suffice.

In thin section, the black obsidians show beautiful fluidal banding owing to the alignment of minute augite rods, acicular microliths of feldspar, and curved black trichites. Compared with most of the andesites, the Llao Rock and other dacites are relatively poor in phenocrysts. The main porphyritic mineral is plagioclase, marked by oscillatory zoning and ranging in composition from acid andesine to acid labradorite. Next in importance is augite, then hypersthene, and lastly a few small crystals of green and brown hornblende, apatite, and ore.

Locally, the black obsidian is traversed by red and chocolate-colored streaks. These are distinctly more porous than the enclosing lava, and apparently owe their origin to gas concentration and oxidation.

Here and there, particularly in the center of the flow, the Llao dacite has a dull-gray color and lithoidal appearance, where the base, instead of being clear glass, is composed of cryptofelsite charged with abundant streams of acicular feldspar.

Although the Llao lava is thus a pyroxene dacite poor in hornblende, all the basic inclusions examined from it are rich in hornblende. These inclusions vary from a few millimeters to a few inches in diameter, and are characterized by a peculiar "pseudo-lamprophyric" texture, like the basic inclusions in the dacites of the Lassen region.

### *The Grouse Hill Dacite*

Patton termed the Grouse Hill lava an andesitic dacite. Chemical analysis (no. 22) shows clearly, however, that the lava is an acid dacite almost identical with the flow of Llao Rock. The analyzed sample is representative of the dark-gray and black glassy phase of the flow, and has the following content: clear glass, with swarms of subparallel trichites and belonites, presumed to be oligoclase and augite, 73 per cent; corroded and glass-charged, zoned phenocrysts of andesine-labradorite, 20 per cent; phenocrysts of brownish-green hornblende, 2 per cent; augite, 2 per cent, and hypersthene, 1 per cent; granular ore, 2 per cent.

The duller, lithoidal parts of the flow contain little or no glass and have a groundmass composed largely of microlithic oligoclase laths and interstitial cryptofelsite.

### *The Cleetwood Dacite*

In general, the top and bottom of the Cleetwood flow are composed of glistening black obsidian. Locally, this glassy part of the flow is crowded with pink spherulites; elsewhere, the jet-black glass is streaked in shades of red and brown owing to oxidation of iron along zones of brecciation and gas concentration. The center of the flow and the feeder, on the other hand, consist mainly of pale-gray, lithoidal, and somewhat more vesicular dacite.

Whether obsidian or holocrystalline, the Cleetwood lava is a hypersthene dacite with accessory augite and hornblende. In other dacite flows erupted from the Northern Arc of Vents, basic inclusions are rare; in the Cleetwood flow, they are almost completely wanting. As in all the younger dacite flows, the content of ferromagnesian crystals is very low as compared with that of porphyritic feldspar. In this respect, the lavas are readily distinguished from the andesites of Mount Mazama.

### *The Redcloud Dacite*

None of the dacite flows from the Northern Arc of Vents is richer in hornblende and tridymite or is more spherulitic than the thick flow forming the great V-shaped cliff of Redcloud. Lithoidal, cryptocrystalline material is much less abundant than in the dacites just described. By far the bulk of the Redcloud dacite is composed of clear, colorless glass, though much of the flow shows a fine banding of vitrophyric and pilotaxitic layers. The content of phenocrysts varies from almost nil to approximately 10 per cent. Hornblende locally forms as much as 5 per cent of the total volume. Hypersthene generally follows in the order of abundance; augite is always subordinate. Zoned phenocrysts of andesine-labradorite, up to 5 mm. in length, normally exceed the combined ferromagnesian minerals in volume.

### *Dacites of Cloudcap and Scott Bluffs*

On the map, plate 3, all the lavas of Cloudcap and Scott Bluffs have been classed as dacite. It must be admitted, however, that some flows in this vicinity may well be andesitic and many more show features intermediate between those of the dacites and the andesites. Few of the rocks of the Crater Lake region are more troublesome to identify. There can be no doubt, however, that the lavas of questionable character terminate close to the park boundary, for to the east the flows are obviously true dacites. If the lavas are rich in colorless glass, contain hornblende, and yet are poor in dark constituents, and if at the same time they show delicate flow banding, they are almost certainly dacites; where, on the other hand, the banding is inconspicuous, the pyroxenes are large and plentiful, and the groundmass is coarsely pilotaxitic, they may be acid andesites. None of them carries porphyritic quartz.

Among the flows which are almost certainly dacitic is the one just inside the rim of the caldera, above Cottage Rock. The base of this sheet passes downward gradually into welded dacite tuff, the presumption being that the lava was erupted immediately after a violent explosive outburst. This flow has a hyalopilitic texture. On an average, phenocrysts of andesine-labradorite constitute approximately 15 per cent of the bulk. Among the dark phenocrysts, which are only about a third as plentiful, augite predominates. Hypersthene comes next. Oxyhornblende is either absent or present only in very minor amount. An interesting feature of all these ferromagnesian minerals is the fact that the unaltered interior of the crystals is commonly enclosed by a zone which is discolored in shades of red and brown, and this in turn is surrounded by a shell composed of opaque ore. These alterations may have been produced by the same hot vapors which gave rise to the abundant spheroids of cristobalite lining some of the vesicles. To these same vapors one may also ascribe the tiny flakes of hematite and brown blotches dispersed in the hyalopilitic groundmass.

Fan-shaped twins of tridymite are invariably present in the dense, pilotaxitic "andesitic dacites," and in some specimens cristobalite may be found on the walls of vesicles. Plentiful and large, stout prisms of hypersthene and augite emphasize the andesitic appearance. Yet in a single exposure, rocks of this kind merge into the more fluidal and glassy dacitic types.

### *Dacites of Anderson Bluffs*

The thick flows of friable, pale-gray dacite which outcrop within the park on the south slope of Mount Scott are in all particulars identical with the dacite domes and flows to the east of Mount Scott, discussed in the following section.

## Domes and Flows East of Mount Scott

Except for the andesite forming the dome of Dry Butte, all the flows and domes beyond the eastern base of Mount Scott are composed of microvesicular pyroxene dacite. Since none of them were discussed by Patton, it seems advisable to summarize their principal features.

The andesite of the Dry Butte dome (analysis no. 17) is the only true hornblende andesite known among the surface extrusions of the Crater Lake region. Such lavas are in fact extremely rare in the southern part of the High Cascades. Hornblende andesite forms the summit dome of Rustler Peak and the Black Butte dome at the west base of Mount Shasta, but these are the only occurrences so far recognized throughout a distance of 80 miles. Thayer has likewise remarked on the paucity of hornblende-bearing andesites in the north-central High Cascades of Oregon. There, also, they were erupted as viscous flows or domes. Again, the plugs (domes) of Mount St. Helens are rarely devoid of hornblende. The mineral, therefore, seems to be typical of the viscous, acid andesite and dacite protrusions of the Cascade belt.

The andesite of Dry Butte is a dense, pale-gray to pink lava carrying abundant prisms of oxyhornblende up to 3 mm. in length. In some samples, the mineral constitutes as much as 10 per cent of the volume. Many of the crystals are bordered by magnetite, some are entirely replaced by ore, and a few are pseudomorphed by a granular mosaic of augite and magnetite. Accompanying the oxyhornblende are small, well terminated prisms of strongly pleochroic hypersthene and anhedral grains of green augite. Together these accessories make up approximately 2 per cent of the whole. One-third of a typical sample is composed of large plagioclase phenocrysts, marked by intense oscillatory zoning, marginal embayments, and spongy inclusions of glass. In composition, these phenocrysts range from labradorite to acid andesine. The remainder of the rock consists of a dense pilotaxitic groundmass of microlithic oligoclase with intergranular pyroxene and ore, and abnormally abundant cristobalite and ?tridymite.

Occasional small crystals of oxyhornblende have been observed in some of the dacites east of Mount Scott, but even where they are present they are far subordinate to pyroxene. The typical dacite of both the domes and the flows is a pale-gray, crumbly, almost pumiceous, and highly porphyritic lava, characterized by large zoned crystals of andesine-labradorite (25–35 per cent), and smaller prisms of hypersthene and augite (5 per cent). Usually the two varieties of pyroxene are equally developed, but where this is not the case, hypersthene predominates.

The main difference between the dacites is in the nature of the groundmass. Though none now contain glass, it is likely that in most the finely crystalline matrix is a product of devitrification, for perlitic cracks are widespread. In many samples, the matrix appears to be a cryptofelsite crowded with tiny microliths of oligoclase, irresolvable trichites, and specks of cristobalite. In others, the base consists of fibrous and brownish positive spherulites up to 5 mm. across, separated by clearer, micrographic areas that seem to be composed of feldspar and tridymite. Wherever open cavities exist, they are almost invariably lined in part by cristobalite.

Basic inclusions in the dacites are both rare and small, and resemble those already described from among the andesites of Mount Mazama.

## Welded Dacite Tuffs (Ignimbrites)

From the standpoint of the petrographer, perhaps the most interesting rocks on the caldera wall are the welded tuffs. A younger series forms the topmost cliffs between Pumice Point and Skell Head; an older, interandesitic series is exposed in the Cottage Rock section, on the cliffs above Cloudcap Bay. They are all characterized by fine, streaky banding and by the presence of wisps, clots, and lenses of glistening, black obsidian in a buff, brown, or pinkish matrix. In one place, the obsidian predominates by far; in another, the varicolored matrix carries only a few small bands of obsidian. No matter which type is subordinate, the rocks show such beautiful fluidal banding that they might readily be mistaken for lavas. Indeed, Diller was so doubtful about their origin that he compromised by referring to them as tuffaceous dacitic lava. Patton, in his description of the younger series, spoke of them as "the Wineglass flow."

In passing from lower to higher ground, the finely laminated, lava-like tuffs merge into more or less incoherent varicolored pumice tuffs and tuff breccias devoid of obsidian streaks. Similarly, they grade downward into a basal layer composed of pulverulent lump pumice. The inference seems justified that the finely banded rocks represent pyroclastic ejecta firmly welded by reason of high temperature, high gas content, and the weight of overlying material. Microscopic study serves to confirm this interpretation.

In thin sections of typical samples from the brim of the Wineglass, the streaks of obsidian, which appear black in the hand specimen, are seen to be composed of clear, colorless glass finely interlaminated with gray glass choked with trichites, globulites, and irresolvable dust. There is no sign of devitrification. The stream lines may be gently curved or bent into the most complex swirls and eddies. Commonly they are tightly molded around phenocrysts. The latter constitute approximately a quarter of the total volume. Plagioclase is four or five times as plentiful as all the other phenocrysts combined. Medium andesine is the dominant variety, but all the crystals are strongly zoned in an oscillatory fashion, and the full range in composition is from acid labradorite to acid andesine. All are much corroded and charged with inclusions of glass. Next in importance among the porphyritic minerals is pale-green augite. Hypersthene is quite subordinate; reddish-brown oxyhornblende and granular ore are minor accessories.

These minerals recur in about the same proportions in the buff and pink matrix between the streaks of obsidian. Viewed by reflected light, the varicolored matrix contrasts vividly with the obsidian, for whereas the latter appears gray, the former appears a bright rusty red, on account of dusty hematite. Here and there the obsidian streaks have frayed ends and merge indefinitely into the matrix, but usually the two are sharply separated. The outstanding feature of the matrix, however, is its unmistakably pyroclastic character, for it is composed of densely packed shards of glass and interstitial glass dust. In normal vitric tuffs, the glass shards lie at random; here, on the contrary, they show a distinct alignment. Many were obviously flattened while still plastic, and some show distortion from having been squeezed between neighboring crystals. In other words, this is a pyroclastic rock showing the results of deformation prior to solidification. The obsidian streaks represent deformed clots of magma, and the matrix represents fine magmatic spray and pulverized glass dust. Together the constituents descended the slopes after the manner of a glowing avalanche, and suffered plastic flow.

The welded tuff bands of the Cottage Rock section are generally more porphyritic and contain more hypersthene. Other minor differences are the absence of oxyhornblende, and the development locally of an autobrecciated appearance, caused by the break-up of glass lapilli and bombs into angular fragments.

No analysis of the Cottage Rock tuff is available, but the one reproduced from Diller's monograph (no. 19) shows that the tuff of the Wineglass is a typical dacite.

### Timber Crater Lavas

If the presence of olivine is regarded as a criterion for the recognition of basalts, then certainly most of the lavas of the Timber Crater volcano must be classified as such. Nor is there much doubt that the field geologist would agree to the use of the name, for the lavas are dark-gray to black, vesicular flows in which little but olivine and minute glassy feldspars can be recognized with the hand lens. Yet the only specimen analyzed from this volcano (no. 12) must be classed chemically as an andesite. The best solution of the problem is perhaps to refer to the rocks as olivine-bearing basaltic andesites. As such they resemble the lavas of the Union Peak volcano and the pre-Mazama flows in the northwest corner of the park. In other words, the pre-Mazama type of lava continued to escape long after the hypersthene andesite cone of Mazama had begun to develop.

Patton described the Timber Crater lava as a "fluidal-interstitial basalt" with almost no olivine and with hypersthene distinctly the dominating pyroxene, but apparently he examined only a single thin section. More extensive study shows that whereas a few flows contain no olivine, by far the majority do include this mineral and in some flows it constitutes as much as 10 per cent of the volume.

The olivine-free lava from the southeast base of Timber Crater has the following content: stumpy, glass-charged, and embayed laths of labradorite, 55 per cent; euhedral prisms of hypersthene, some of which have jackets of augite, 15 per cent; brownish-black glass stippled with granules of ore, 30 per cent.

Contrasted with this are the pale-gray flows on the north slope of the volcano. Though these are also rich in deep-brown glass (15 per cent), they carry abundant phenocrysts of olivine. Hypersthene is present as smaller euhedral microphenocrysts, but augite is restricted to minute, ragged granules. In the "cinders" of the summit cone, augite is altogether absent, whereas hypersthene is unusually abundant. Here, as in the quickly chilled "cinders" of other cones, glass makes up almost half the total volume.

Finally, in the analyzed specimen (no. 12) from the southwest flank of the volcano, olivine phenocrysts constitute 3 per cent, hypersthene is by far the dominant ferromagnesian, and augite is restricted to the dense, intergranular base. The feldspar varies little in composition from medium labradorite. Cristobalite, which is rarely absent from any of the Timber Crater flows, is plentifully sprinkled on the walls of vesicles.

## CINDER CONES AND ASSOCIATED FLOWS

In this section, our concern is with the andesitic and basaltic products of the parasitic cones active at about the same time as the Northern Arc of Vents, and with the products of the final activity of Mount Mazama, namely the cinder cone and flow of Wizard Island.

Most geologists, seeing these rocks in the field, would not hesitate to classify them as basalts. The truth is, however, that whereas olivine basalts do occur among them, the majority are more properly to be spoken of as basaltic andesites, "basaltic" on account of their texture and the presence of considerable olivine, but "andesites" on account of their chemical composition. Since they resemble the pre-Mazama lavas within the park and the products of the Union Peak volcano, a brief account will suffice.

### *Crater Peak*

Among the analyzed ejecta of the parasitic cones in question are those of Crater Peak (no. 10). The specimen selected for analysis is typical of the scoriaceous ejecta (cinders) of this vent. It is an olivine-rich, hyalopilitic basaltic andesite. Approximately 45 per cent of the rock consists of deep-brown glass charged with dusty and granular ore. Approximately 30 per cent is composed of slender microliths of andesine. Zoned phenocrysts of labradorite, many with concentric inclusions of glass and thin, clear rims of andesine (5 per cent), fresh olivine crystals (8 per cent), granular augite (10 per cent), and accessory hypersthene (2 per cent) make up the remainder.

Several flows issued from the flanks of Crater Peak. Some are pale gray, massive, and almost holocrystalline; others are black, scoriaceous, and rich in glass. In different flows and even in different parts of a single flow, the proportion of the several ferromagnesian minerals varies considerably.

### *Diller Cone*

The scoria, agglutinate, and red-crusted lavas near the summit of this cone are typified by plentiful phenocrysts of olivine (5 per cent) and labradorite (25 per cent). In the sections examined, glass is either absent altogether or present only in small amount, the groundmass having a dense intergranular texture made up of slender laths of andesine separated by irregular grains of augite and ore.

### *Cones Bordering Pumice Flat*

The cinder cones near the east base of the Union Peak volcano are located on a fissure radiating from the former summit of Mount Mazama. Although this is taken to mean that they were fed from the reservoir beneath Mount Mazama, their products are similar to those of the older Union Peak volcano. In other words, they are olivine-bearing basaltic andesites varying in texture from hyalopilitic through intergranular to subophitic.

### *Desert Cone and Bald Crater*

The scoriaceous bombs and lapilli, as well as the lavas, erupted from Desert Cone are invariably rich in porphyritic olivine (5 to 10 per cent). In fact, they include the most olivine-rich flows within the Park. No chemical analyses are available, but the majority of the products of this vent are probably true basalts and the remainder are transitional toward basic andesites.

In general, as might be anticipated, the pyroclastic ejecta contain more glass than the flows, some of which are holocrystalline and intergranular. Where the lavas and fragmental ejecta have been reddened by gas action, the olivine is commonly replaced in large part by granular ore and hematite.

### *Red Cone*

The most basic rock yet analyzed from the park comes from a flow at the southeast base of Red Cone (no. 9), but whether it issued from the cone itself or is part of the pre-Mazama basement is debatable.

Patton has already devoted much attention to the textural variations of the Red Cone rocks, and his observation that they are almost all olivine-rich and hypersthene-poor is here corroborated. An analyzed specimen from the flow has approximately the following content: microliths of labradorite, 50 per cent; intergranular specks of augite, 30 per cent; brown, interstitial glass, 10 per cent; fresh, porphyritic olivine, 5 per cent; granular ore, 5 per cent. Cristobalite is plentiful. Distinctive of the rock is the absence of porphyritic feldspar.

In most flows, olivine is easily detected even by the unaided eye on account of its pale-green color. Not uncommonly, however, and particularly where the lavas are reddish or brown instead of gray or black, the olivine has a ruddy, iridescent tint. Thin slides of such lavas show that the olivine is partly altered to serpentine and hematite, and the associated grains of ore are also filmed with hematite dust. Tridymite occurs in the dense base of these altered lavas, and its origin, like that of the hematite, may be ascribed to the activity of residual vapors.

Though most of the flows from Red Cone are either devoid of large crystals of feldspar or only sparingly dotted by them, some of the pyroclastic ejecta carry zoned phenocrysts of basic labradorite in large amount. Moreover, though most of these ejecta are as rich in olivine as the lavas, there are some in which the mineral is virtually absent. In such rocks, its place is taken by small prisms of hypersthene.

### *Forgotten Crater*

The lavas and "cinders" described thus far are somewhat monotonous in their similarity, and it comes as a welcome relief to examine the flows erupted by Forgotten Crater. The cone itself is composed of normal olivine-bearing basaltic andesite scoria and lithic fragments. From its western base there escaped a long flow. Except near the source, this also is composed of olivine-bearing, vitrophyric and scoriaceous basaltic andesite (analysis no. 11). Approximately, its content is as follows: deep-brown glass, with dusty ore and trichites, 35 per cent; glass-charged, corroded phenocrysts of basic labradorite and microliths of andesine, 45 per cent; porphyritic and intergranular augite, 12 per cent; equal amounts of porphyritic olivine and hypersthene, 4 per cent; granular ore, 4 per cent. Within the flow lie ovoid xenoliths of Mazama andesite and more numerous inclusions of pre-Mazama lava.

Close to its source this western stream of lava and the short flow which spilled over the south rim of the crater show a peculiar banded, composite character. Layers of dark olivine-bearing basaltic andesite alternate with layers of pale-gray, highly pumiceous lava from a few millimeters to a few inches in width. Xenoliths of cristobalite-rich, pre-Mazama andesite are common to both. In the field the dark and light layers are sharply defined, and in thin section the contrast is no less striking. Whereas the glass in the dark lava is deep brown, the glass in the pale bands is colorless and extremely vesicular, is commonly traversed by perlitic cracks, and carries swarms of belonites, probably of oligoclase. In this glass, which constitutes approximately two-thirds of the pale lava, lie zoned phenocrysts of andesine-labradorite (up to 20 per cent), and crystals of augite (3–9 per cent), hypersthene (2–3 per cent), ore (2 per cent), and brown oxyhornblende (1 per cent). Seen apart from the associated olivine-bearing, dark andesite, this pale lava would be classed immediately with the dacites erupted from the Northen Arc of Vents.

It seems, therefore, that during the closing stages of its activity, Forgotten Crater, which had formerly erupted nothing but olivine-bearing basaltic andesite, began to erupt, in addition and simultaneously, dacitic lava distinguished by colorless glass, more acid feldspar, the absence of olivine, and the presence of hornblende. These two magmas showed no tendency to mix though they were finely interlaminated.

This eruption of two distinct types of magma from a common source serves again to emphasize the fact that throughout most of its long history Mount Mazama, like Mount Shasta, erupted little but hypersthene andesite. During its waning stages, on the other hand, the principal products were dacite and olivine-bearing basaltic andesite and basalt.

### *Wizard Island*

The lavas of Wizard Island have a decided basaltic appearance in the field, and in thin section the abundance of ferromagnesian crystals and the dark color of the interstitial glass distinguish them clearly from the typical andesites of Mount Mazama. Yet analysis (no. 13) shows that the Wizard Island lavas are also andesites.

Almost all of them are hyalopilitic hypersthene-augite andesites with accessory olivine. Exceptionally, they may be holocrystalline. But the chief interest of the lavas is the presence in them of sporadic inclusions. There are, as in most of the flows related to cinder cones, xenoliths of older andesite and basalt, but these, being quite unaltered, merit no discussion. Here and there one may find white or pale-gray, sugary, and vesicular inclusions from a fraction of an inch to 4 feet in diameter. Some of these are so cellular as to resemble pumice. Under the microscope, many are seen to be composed almost entirely of colorless glass (R.I., 1.492–1.497) in which lie partially vitrified phenocrysts of labradorite up to 2 mm. long. Accompanying the vitrified feldspar are occasional prisms of hypersthene and augite and granules of ore around which the glass is commonly stained brown, though the minerals themselves appear to be unaffected. Occasionally the vesicular glass is cut by veins of quartz mosaic. The inference is that these cellular, glassy inclusions represent partially dissolved feldspathic (dioritic to gabbroid) clots picked up and metamorphosed by the enclosing lava. Rarely one finds, in addition to the well defined inclusions, irregular strings of similar material, as if, locally, the glass produced by solution of the feldspars was rendered sufficiently fluid to be streaked parallel to the banding of the surrounding lava.

With these vitrified inclusions, there are occasional pale-gray inclusions of dioritic or gabbroid appearance. These are composed chiefly of large, finely twinned phenocrysts of acid labradorite, separated by slender laths of andesine, granular ore, biotite, a little hypersthene, and less augite. The dark constituents form but a small part of the whole. Presumably these coarsely crystalline feldspathic inclusions represent fragments torn from the margins of the underlying magma chamber, and the vitrified, pumiceous inclusions are the result of their partial solution. Patton has described somewhat similar rocks among the ejecta of the culminating eruptions of Mount Mazama, under the title "light-colored granophyric secretions." These are the only rocks of the Crater Lake region which are known to contain biotite.

## DIKES

### *Dacite Dikes*

Most of the dikes on the walls of Crater Lake are composed of pyroxene andesite; only two are of dacite. These two dikes cut across the cliffs immediately beneath Llao Rock, and Diller maintained that the more westerly was one of the feeders of the Llao lava. Elsewhere, however, evidence has been offered to indicate that this dike is not a feeder to the Llao lava, but an offshoot from a conduit common to both.

The dike in question varies between 6 and 7 feet in width. For a distance of approximately 6 inches from the edge, it consists of well banded black obsidian, composed of alternating layers of light- and dark-brown glass crowded with microliths of oligoclase and augite and with varicolored globulites. Scattered throughout are corroded phenocrysts of basic plagioclase, together with a few crystals of hypersthene and augite and occasional prisms of green hornblende.

The interior of the dike is strikingly different, being pale gray and holocrystalline. By far the bulk consists of dense cryptofelsite heavily charged with clouds of trichites and globulites. Zoned phenocrysts of feldspar (labradorite-andesine) up to 2 mm. in length (12 per cent), slender prisms of hypersthene (2 per cent), green hornblende (1 per cent), granular ores, and scanty apatite are distributed throughout. But perhaps the most interesting feature of the center of the dike is the fact that it is much more vesicular than the glassy margins and that the vesicles carry abundant tiny spheroids of cristobalite. In some samples, indeed, cristobalite constitutes almost 5 per cent of the total volume.

The second dacite dike beneath Llao Rock shows an inward passage from black obsidian through pale-gray, almost pumiceous lava, to a core of darker-gray and much more strongly banded dacite. The obsidian selvage, seen under the microscope, appears as a pale-buff glass charged with trichites of plagioclase and ?augite, and carrying phenocrysts of zoned andesine-labradorite (12 per cent), olive-green hornblende, and hypersthene (together, 3 per cent). No cristobalite was detected.

Within an inch or two, this obsidian merges into microvesicular dacite. Locally the two are interlaminated. In proportion, size, and nature, the phenocrysts are identical with those in the obsidian, but the groundmass contains either no glass at all or at most an insignificant amount, being composed of an irresolvable, cloudy cryptofelsite. Most of the vesicles are empty, but a few carry grains of cristobalite.

The dark-gray core of the dike is particularly distinguished by two features: first, a strong fluxion structure, caused by the parallel orientation of swarms of oligoclase microliths in the cryptofelsitic base; second, the abundance of cristobalite lining vesicles.

Briefly, then, this eastern dacite dike shows an inward transition from a glassy skin to increasingly coarse, holocrystalline lava, and a corresponding increase both in vesicularity and in the content of cristobalite. Throughout the dikes are scattered inclusions, some of them true xenoliths of hyalopilitic hypersthene andesite, and some pseudo-lamprophyric segregations like those common in the adjacent flows.

### *Andesite Dikes*

It would serve no good purpose to describe in detail the petrographic characters of the andesite dikes, since they closely resemble the andesite flows already discussed. Certain features, however, are worthy of mention.

Three dikes of andesite are exposed on the walls of Steel Bay. The easternmost of these has margins of black, glassy lava. The core, on the other hand, consists of almost holocrystalline, pale-gray andesite. Viewed in thin section, the paler core is seen to be made up largely of a dense pilotaxitic felt of oligoclase microliths and specks of augite with a small amount of interstitial glass (55 per cent). In this matrix lie phenocrysts of bytownite-andesine (30 per cent), granular ore (5 per cent), hypersthene (6 per cent), and augite (2 per cent). The pale core is somewhat more vesicular than the glassy selvage, and many of the vesicles are coated with crystals of cristobalite (2 per cent). The selvage, on the contrary, contains no cristobalite.

West of this dike is a much larger intrusion which connects in its upper part with a long flow of lava. This intrusion is distinctive in having no glassy selvage and in carrying unusually abundant and large basic inclusions. Locally these inclusions are as voluminous as the enclosing andesite. The latter is a pilotaxitic hypersthene-augite andesite, and except in one particular does not differ from the normal andesite flows. This exceptional feature is the presence of abundant wedge-shaped twins of tridymite which partly fill cavities. In one section, the mineral constitutes as much as 3 per cent of the whole. Cristobalite, on the other hand, is absent.

The inclusions in this dike are very porous. Their texture is best described as diktytaxitic and pseudo-lamprophyric. Essentially, they are composed of a crisscross felt of labradorite laths (65 per cent), slender hypersthene prisms partly rimmed by secondary ore and occasionally enclosed in jackets of augite (15 per cent), stumpy prisms of augite (5 per cent), and granular magnetite (5 per cent). Between these is a matrix partly made up of devitrified glass (2 per cent), but mainly of tridymite (6 per cent) and cristobalite (2 per cent). The occurrence of both forms of silica in the inclusions is thus in contrast with the development of tridymite alone in the enclosing andesite.

The third dike on the walls of Steel Bay also served as a feeder to a surface flow. This differs from the preceding chiefly in having a glassy selvage and pale, vesicular, holocrystalline core, and in being almost wholly devoid of basic inclusions.

Of all the dikes on the caldera walls, the most conspicuous and thickest is the Devil's Backbone. Like the dike just mentioned, it gradually changes from coarsely pilotaxitic in the center to hyalopilitic toward the margins, and is invariably rich in microlithic oligoclase. In the same direction there is a diminution in the number of cristobalite crystals lining the vesicles. Few of the Crater Lake dikes contain this mineral in greater abundance. From the analysis of a sample of the Devil's Backbone (no. 15), the similarity of the dike rock to the andesite flows is immediately apparent.

The dike on the wall of Grotto Cove is essentially like the Devil's Backbone. So are the two dikes on the walls below Sentinel Point and the one below Sun Notch, except that they lack both tridymite and cristobalite, and occasionally carry olivine.

Another dike, particularly interesting on account of its alteration, is the one which descends to the edge of the lake at Eagle Point. Most of this intrusion consists of dense, black andesite. In thin section, half of the rock is seen to be composed of devitrified glass rendered almost opaque by dusty ore. Almost as voluminous are large, spongy zoned phenocrysts of andesine-labradorite. The remainder is made up of hypersthene prisms (5 per cent) partly altered to ?bowlingite, less altered crystals of augite (3 per cent), and rare grains of olivine. Contrasting strongly with this dark andesite is a pale sage-green "propylitic" type which is largely confined to the margins of the intrusion. Normally, as we have seen, the edges of dikes are finer-grained than the interior, but here the reverse is true. Moreover, the pyroxene crystals, and especially those of hypersthene, are more thoroughly altered to serpentine than in the central part of the dike. Calcite is sprinkled throughout, particularly along cracks in the porphyritic feldspar. Finally, the joint faces are lined locally with opal and radiating prisms of quartz. Since in most other dikes it is the central part which is most altered, it may be supposed that the changes visible in the Eagle Point intrusion are the result, not of the concentration of residual solutions during solidification, but of later solfataric action which has similarly affected the neighboring lavas.

## PUMICE AND SCORIA OF THE CLIMACTIC ERUPTIONS

In the culminating eruptions of Mount Mazama, two radically different types of magma were involved. Throughout most of the activity, pale-gray, buff, and white dacite pumice was erupted; in the concluding stages, the ejecta consisted of dark-gray and black basic scoria.

### *Dacite Pumice*

Except for the degree of sorting and the size of the fragments, the granular pumice that fell from the air during the first stages of activity does not differ from the more voluminous pumice erupted later in the form of glowing avalanches. Together, these pumice deposits constitute more than seven-eighths of the total volume of fresh magma erupted.

Both mineralogically and chemically, the dacite pumice is almost identical with the dacitic lavas erupted at an earlier date from the Northern Arc of Vents. In other words, the pumice is composed of glassy hypersthene-augite dacite with accessory hornblende. Variations in crystal content and in the ratio of light to dark minerals have already been discussed.

The glassy base of the pumice is highly vesicular. Indeed, the density of large bombs may be as low as 0.50. When the pumice is pulverized artificially, its density may not exceed 2.0, showing that even the fine pumice dust is minutely vesicular. So frothy is some of the pumice and so elongated are the vesicles that the fragments appear like delicately shredded glass.

Typically, the glass is colorless and has a refractive index between 1.500 and 1.510. Occasionally it is pale yellow or buff, and in large bombs with oxidized crusts it may appear pale pink by reflection, perhaps because of dusty hematite. Trichites and belonites are exceptional.

The content of crystals varies between wide limits, the average lying between 10 and 15 per cent by volume. In some samples, the content falls below 1 per cent; in a few, it rises as high as 60 per cent. Such irregular concentration is only to be expected among ejecta derived by eruption of magma undergoing crystallization.

Few crystals exceed 2 mm. in length, and few measure less than 0.2 mm. By far the majority range in size between 0.5 and 1 mm. Plagioclase is almost invariably more abundant than all the ferromagnesian minerals combined. Most of the feldspars are intensely zoned in an oscillatory fashion, and some show a range in composition from labradorite at the center to oligoclase at the rims. Equally striking is the abundance of glassy inclusions. These are more plentiful than in the feldspars of the dacitic lavas, and may be so numerous as to give the crystals a spongy appearance. Characteristic also is the highly cracked nature of the feldspar.

Of the dark constituents in the pumice, hypersthene is usually the chief. Rarely it is exceeded in amount by pale-green augite, and still more rarely by hornblende. Occasional crystals of hornblende may have a deep-red color and low extinction angle, but typically the mineral varies in color from olive green to brownish green and has an extinction angle, Z to c, of about 15°. Resorption of hornblende and consequent formation of magnetite rims, a feature characteristic of the hornblende which occurs sparingly in the basic inclusions and andesites of Mount Mazama, is completely absent in the dacite pumice. Olivine has not been observed. Magnetite, on the other hand, is ubiquitous, though sparsely distributed. Tridymite and cristobalite, though plentiful among the dacitic lavas, have not been detected in the pumice.

### *Basic Scoria*

Immediately after the dacitic part of the magma chamber had been erupted, it was followed by much darker, more crystalline, and more basic scoria, in the form of *nuées ardentes*. The change, it should be emphasized, was sudden. The silica content of the dacite pumice ranges from 66.38 to 69.85 per cent; that of the basic scoria ranges from 53.94 to 56.85 per cent. In fact, the composition of the basic scoria approximates closely that of the pre-Mazama basaltic andesites and that of the parasitic cinder cones, though the mineral content is strikingly different.

The typical basic scoria is marked by an abundance of dark-brown, vesicular glass and by plentiful crystals. Two scoria bombs were selected for analysis (nos. 26 and 27). One of these came from the walls of Llao's Hallway, a narrow chasm tributary to Castle Creek. This has the following content: broken and glass-charged phenocrysts of zoned andesine-labradorite, 40 per cent; prisms of hornblende, showing pleochroism from pale yellow, X, through yellowish green, Y, to deep olive green, Z, and extinction angles up to 23° (Z to c), and occasionally with cores of fresh olivine, 15 per cent; granular ore, 3 per cent; vesicular brown glass, with a refractive index of 1.531±0.002, 42 per cent. Other scoria bombs from the same locality carry up to 4 per cent of hypersthene and 1 per cent of augite. The ratio of the various minerals differs within wide limits, the percentage of feldspar occasionally falling below 10 and that of hornblende sometimes rising to 30.

The second bomb analyzed came from the deposits in Sun Creek canyon. This is of an unusual type. The glass is paler than in most bombs and has a refractive index of 1.528 to 1.532. Approximately 60 per cent consists of intensely zoned plagioclase ranging in composition from andesine to medium bytownite. Small prisms of augite and hypersthene, in roughly the same proportions, together make up 10 per cent of the whole. Granular ore constitutes another 5 per cent. The principal feature of the bomb is the unusual paucity of hornblende, less than 1 per cent.

Rarely, bombs may be found which show a strongly banded structure, streaks of white pumice from a hair's breadth up to an inch across running through the black scoria. Specimens were found in Annie Creek canyon and on the Pumice Desert. The light and dark parts are sharply delimited. To judge from the refractive indices, 1.507±0.002 for the light bands and 1.530±0.002 for the dark, it seems that the bombs are composed of both dacite and basic andesite. In the dark bands the phenocrysts are basic feldspar, hornblende, accessory hypersthene, augite, and ore; in the light bands the same minerals recur in roughly the same proportions, but are less than half as numerous. Apparently both types of magma were for a time erupted simultaneously without mixing.

In brief, the basic scoria differs from the preceding dacite pumice in the much greater content of ferromagnesian minerals, particularly hornblende, the presence of considerable olivine, the more basic composition of the feldspar, and the dark-brown color of the glass. Exceptionally the hornblende has the reddish color and low extinction angles of oxyhornblende, but normally it is green or greenish brown and never shows marginal separation of magnetite.

The matrix of the scoria flows consists partly of the same materials as the bombs. This part was obviously produced by shattering of the larger lumps during transit. The remainder consists of small lithic fragments.

Study of the lithic fragments in thin sections and with the binocular reveals the following types: (*a*) hypersthene andesites similar to those exposed in the caldera walls, composing by far the bulk; (*b*) many opalized chips of andesite, possibly derived from solfataric areas about the former summit of Mazama; (*c*) intergranular and hyalopilitic olivine-bearing basaltic andesites like those of the Union Peak volcano and the pre-Mazama lavas in the northwest corner of the park; (*d*) various types of obsidian identical with those erupted from the Northern Arc of Vents; (*e*) devitrified, tridymite-rich dacites comparable with the southern dacites; (*f*) epidote(?)-bearing quartz keratophyres and chips of propylitized lavas similar to those of the Western Cascade volcanic series. Thus, with the exception of the last-named fragments, which are extremely rare, all the lithic inclusions were derived from shallow depths, that is, from the Pliocene basement beneath Mazama and from the cone of Mazama itself. At no High Cascade volcano known to the writer have fragments of the pre-Tertiary basement ever been discovered among the ejecta.

Some of the scoria flows were almost entirely composed of crystals. For instance, after the lithic-rich flows had deposited their load in the Pumice Desert they were followed by avalanches consisting almost exclusively of hornblende and plagioclase crystals with accessory pyroxenes, ore, and a little brown glass. These avalanches were presumably among the latest, and they suggest that at the close of the eruptive cycle deep-seated, crystal-rich levels in the magma chamber were beginning to be tapped.

After they had come to rest, the scoria deposits were subjected to long-continued fumarolic action. Gases, temporarily trapped in the quickly compacted ejecta, escaped along irregular, though more or less vertical, joints. The nature of these gases is not known, but probably they included much ferric chloride. Reacting with air and percolating ground waters, they deposited iron oxides close to the surface. The walls of the fumarole cracks and the upper layers of the scoria deposits were deeply reddened with hematite, most of which has subsequently been converted to limonite. In addition, the fumarole cracks are commonly bordered by decomposed scoria in which kaolin and opal are widespread. Finally, it may be recorded that a coating of chrysocolla was found on a slab of scoria in the talus banks below the main falls on Annie Creek. Presumably, therefore, copper was also transported among the fumarolic vapors.

## ANALYSES

### ANALYSES OF OLIVINE-BEARING PRE-MAZAMA LAVAS

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 51.51 | 53.00 | 54.09 | 54.38 | 55.63 | 56.75 | 56.95 | 58.65 |
| $Al_2O_3$ | 17.52 | 18.31 | 18.92 | 17.97 | 17.92 | 18.02 | 18.84 | 18.35 |
| $Fe_2O_3$ | 1.51 | 2.37 | 1.43 | 3.83 | 2.18 | 1.80 | 2.06 | 1.59 |
| $FeO$ | 6.69 | 5.97 | 5.97 | 3.75 | 5.42 | 4.92 | 4.28 | 4.21 |
| $MgO$ | 6.74 | 5.30 | 5.33 | 5.38 | 4.48 | 4.78 | 4.37 | 3.49 |
| $CaO$ | 8.78 | 8.11 | 8.29 | 8.52 | 7.73 | 8.02 | 7.45 | 6.95 |
| $Na_2O$ | 3.34 | 3.92 | 3.83 | 3.37 | 3.73 | 4.04 | 3.89 | 3.70 |
| $K_2O$ | 0.77 | 0.82 | 0.71 | 0.79 | 1.14 | 0.71 | 0.82 | 1.32 |
| $H_2O+$ | 0.49 | 0.27 | 0.03 | 0.55 | 0.10 | 0.40 | 0.31 | 0.70 |
| $H_2O-$ | 0.15 | 0.14 | 0.07 | 0.35 | 0.10 | Nil | 0.19 | 0.20 |
| $TiO_2$ | 1.12 | 1.26 | 1.04 | 0.81 | 1.23 | 0.56 | 0.79 | 0.81 |
| $P_2O_5$ | 0.31 | 0.37 | 0.24 | 0.22 | 0.42 | 0.18 | 0.19 | 0.17 |
| $MnO$ | 0.15 | 0.14 | 0.13 | 0.11 | 0.09 | Trace | Trace | Trace |
| $BaO$ | .... | ...... | ...... | ...... | ...... | ...... | 0.04 | 0.06 |
| Totals | 99.08 | 99.98 | 100.08 | 100.03 | 100.17 | 100.18 | 100.18 | 100.20 |
| *Norms* | | | | | | | | |
| q | 0.12 | 1.32 | 2.10 | 7.26 | 6.18 | 5.70 | 7.68 | 10.92 |
| or | 4.45 | 5.00 | 3.89 | 4.45 | 6.67 | 4.45 | 5.00 | 7.78 |
| ab | 28.30 | 33.01 | 32.49 | 28.30 | 31.44 | 34.06 | 33.01 | 31.44 |
| an | 30.58 | 29.75 | 32.25 | 31.69 | 28.91 | 28.91 | 31.41 | 29.47 |
| wo | 5.80 | 3.25 | 2.90 | 3.71 | 2.90 | 4.18 | 2.09 | 1.74 |
| en | 16.90 | 13.30 | 13.30 | 13.40 | 11.20 | 11.90 | 10.90 | 8.70 |
| fs | 9.50 | 7.13 | 8.32 | 2.51 | 6.20 | 6.60 | 4.87 | 5.02 |
| mt | 2.09 | 3.48 | 2.09 | 5.57 | 3.25 | 2.55 | 3.02 | 2.32 |
| il | 2.13 | 2.43 | 1.98 | 1.52 | 2.28 | 1.06 | 1.52 | 1.52 |
| ap | 0.67 | 1.01 | 0.67 | 0.67 | 1.01 | 0.34 | 0.34 | 0.34 |
| Normative plagioclase | $Ab_{48}$ | $Ab_{53}$ | $Ab_{50}$ | $Ab_{47}$ | $Ab_{52}$ | $Ab_{54}$ | $Ab_{51}$ | $Ab_{51}$ |
| *Niggli values* | | | | | | | | |
| si | 128 | 137 | 141 | 145 | 154 | 157 | 162 | 180 |
| al | 26 | 28 | 29 | 28 | 29 | 29 | 32 | 33 |
| fm | 42 | 38 | 37 | 38 | 36 | 35 | 33 | 31 |
| c | 23 | 23 | 23 | 24 | 23 | 24 | 23 | 23 |
| alk | 9 | 11 | 11 | 10 | 12 | 12 | 12 | 13 |
| qz | −8 | −7 | −3 | +5 | +6 | +9 | +14 | +28 |
| k | 0.13 | 0.12 | 0.11 | 0.13 | 0.17 | 0.11 | 0.13 | 0.19 |
| mg | 0.60 | 0.53 | 0.55 | 0.56 | 0.51 | 0.57 | 0.56 | 0.52 |

1. Olivine basalt, Santiam type (intracanyon flow). Near summit Outerson Mountain. Anal. R. B. Ellestad. T. P. Thayer, "Petrology of later Tertiary and Quaternary rocks of the north-central Cascade Mountains in Oregon," Bull. Geol. Soc. Amer., vol. 48, p. 1622, 1937.
2. Olivine micronorite. Hunts Cove. Anal. R. B. Ellestad. Thayer, *ibid.*
3. Cristobalite micronorite, coarse facies of Minto plug. Anal. R. B. Ellestad. Thayer, *ibid.*
4. Olivine basalt. North base of Union Peak, quarry adjacent to Medford highway. Anal. W. H. Herdsman.
5. Olivine basaltic andesite. Red Blanket Canyon, near south base of Union Peak volcano. Anal. W. H. Herdsman.
6. Olivine micronorite, pale, coarse facies of Union Peak plug. Anal. W. H. Herdsman.
7. Hypersthene-bearing basaltic andesite. Annie Creek, near east base of Union Peak volcano. Anal. H. N. Stokes. J. S. Diller and H. B. Patton, "The geology and petrography of Crater Lake National Park," U. S. Geol. Surv. Prof. Paper 3, p. 161, 1902.
8. Hypersthene-bearing basaltic andesite. Desert Ridge. Anal. H. N. Stokes. Diller and Patton, *ibid.*

NOTE: Nos. 1, 2, and 3 are not Crater Lake rocks.

Analyses of lavas related to cinder cones

| | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|
| $SiO_2$ | 52.99 | 55.83 | 56.32 | 58.72 | 59.39 |
| $Al_2O_3$ | 16.71 | 18.01 | 16.14 | 17.94 | 18.45 |
| $Fe_2O_3$ | 3.80 | 2.63 | 1.47 | 1.98 | 1.79 |
| FeO | 3.55 | 4.07 | 4.98 | 4.51 | 3.90 |
| MgO | 6.95 | 5.12 | 6.16 | 4.46 | 3.13 |
| CaO | 8.49 | 7.40 | 7.78 | 6.44 | 6.29 |
| $Na_2O$ | 3.56 | 3.64 | 3.77 | 3.56 | 4.29 |
| $K_2O$ | 1.29 | 1.22 | 1.54 | 1.01 | 1.29 |
| $H_2O+$ | 0.59 | 0.72 | 0.60 | 0.22 | 0.42 |
| $H_2O-$ | 0.18 | 0.26 | 0.18 | 0.18 | 0.10 |
| $TiO_2$ | 1.18 | 0.84 | 0.93 | 0.80 | 0.41 |
| $P_2O_5$ | 0.42 | 0.11 | 0.19 | 0.25 | 0.22 |
| MnO | Trace | 0.08 | 0.09 | 0.04 | Trace |
| BaO | 0.07 | ...... | ...... | ...... | 0.05 |
| SrO | 0.12 | ...... | ...... | ...... | 0.04 |
| NiO | 0.02 | ...... | ...... | ...... | ...... |
| Totals | 99.92 | 99.93 | 100.15 | 100.11 | 99.77 |
| *Norms* | | | | | |
| q | 2.22 | 6.30 | 3.48 | 12.12 | 10.32 |
| or | 7.78 | 7.23 | 8.90 | 6.12 | 7.78 |
| ab | 29.87 | 30.92 | 31.96 | 29.87 | 36.16 |
| an | 25.85 | 29.19 | 22.52 | 30.02 | 27.24 |
| wo | 5.68 | 2.78 | 6.38 | 0.12 | 0.93 |
| en | 17.40 | 12.80 | 15.40 | 11.10 | 7.80 |
| fs | 1.45 | 4.09 | 6.34 | 5.41 | 5.02 |
| mt | 5.57 | 3.71 | 2.09 | 2.78 | 2.55 |
| il | 2.28 | 1.52 | 1.82 | 1.52 | 0.76 |
| ap | 1.01 | 0.34 | 0.34 | 0.67 | 0.34 |
| Normative plagioclase | $Ab_{54}$ | $Ab_{51}$ | $Ab_{59}$ | $Ab_{50}$ | $Ab_{57}$ |
| *Niggli values* | | | | | |
| si | 135 | 155 | 154 | 175 | 186 |
| al | 25 | 30 | 26 | 31 | 34 |
| fm | 41 | 36 | 39 | 36 | 29 |
| c | 23 | 22 | 23 | 21 | 21 |
| alk | 11 | 12 | 12 | 12 | 16 |
| qz | −9 | +7 | +6 | +27 | +22 |
| k | 0.20 | 0.18 | 0.22 | 0.16 | 0.17 |
| mg | 0.64 | 0.58 | 0.64 | 0.56 | 0.51 |

9. Hypersthene-bearing olivine basalt. Southeast base of Red Cone. May be a pre-Mazama flow. Anal. H. N. Stokes. Diller and Patton, *loc. cit.*
10. Basaltic andesite, near summit of Crater Peak. Anal. W. H. Herdsman.
11. Olivine-bearing basaltic andesite. Main flow from west base of Forgotten Crater. Anal. W. H. Herdsman.
12. Olivine-bearing basaltic andesite. Southwest base of Timber Crater. Anal. W. H. Herdsman.
13. Hypersthene andesite. West edge of Wizard Island. Anal. H. N. Stokes. Diller and Patton, *op. cit.*, p. 94.

ANALYSES OF MAZAMA ANDESITES

| | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|
| $SiO_2$ | 58.48 | 60.09 | 60.98 | 62.06 | 62.09 |
| $Al_2O_3$ | 17.85 | 17.85 | 17.82 | 17.57 | 17.03 |
| $Fe_2O_3$ | 2.67 | 2.03 | 1.83 | 3.53 | 2.38 |
| FeO | 3.29 | 3.45 | 3.33 | 1.41 | 2.69 |
| MgO | 3.61 | 3.50 | 2.67 | 2.73 | 3.08 |
| CaO | 6.81 | 6.28 | 5.73 | 5.44 | 5.65 |
| $Na_2O$ | 3.77 | 4.17 | 4.26 | 3.95 | 4.10 |
| $K_2O$ | 1.23 | 1.31 | 1.43 | 1.28 | 1.67 |
| $H_2O+$ | 0.86 | 0.26 | 0.45 | 1.04 | 0.13 |
| $H_2O-$ | 0.34 | 0.12 | 0.13 | 0.40 | 0.04 |
| $TiO_2$ | 0.69 | 0.54 | 0.71 | 0.54 | 0.65 |
| $P_2O_5$ | 0.17 | 0.23 | 0.17 | 0.19 | 0.19 |
| MnO | Trace | Trace | Trace | Trace | Trace |
| BaO | 0.05 | 0.05 | 0.06 | ...... | 0.07 |
| SrO | 0.05 | 0.05 | 0.05 | ...... | 0.07 |
| NiO | .... | 0.05 | .... | ...... | ..... |
| Totals | 99.87 | 99.98 | 99.62 | 100.14 | 99.84 |
| | | *Norms* | | | |
| q | 12.30 | 11.70 | 13.68 | 18.60 | 15.48 |
| or | 7.23 | 7.78 | 8.34 | 7.78 | 10.01 |
| ab | 31.96 | 35.63 | 36.16 | 33.54 | 34.58 |
| an | 28.08 | 25.85 | 25.02 | 26.13 | 23.07 |
| wo | 1.62 | 1.51 | 1.04 | ..... | 1.74 |
| en | 9.00 | 8.80 | 6.90 | 6.80 | 7.70 |
| fs | 2.64 | 3.70 | 3.43 | ..... | 1.98 |
| mt | 3.94 | 3.02 | 2.55 | 3.02 | 3.48 |
| il | 1.37 | 1.22 | 1.37 | 1.44 | 1.22 |
| hm | .... | .... | .... | 1.06 | .... |
| ap | 0.67 | 0.67 | 0.34 | 0.34 | 0.34 |
| Normative plagioclase | $Ab_{53}$ | $Ab_{58}$ | $Ab_{59}$ | $Ab_{56}$ | $Ab_{60}$ |
| | | *Niggli values* | | | |
| si | 180 | 190 | 205 | 215 | 209 |
| al | 32 | 33 | 35 | 36 | 34 |
| fm | 32 | 30 | 27 | 28 | 29 |
| c | 22 | 22 | 21 | 20 | 20 |
| alk | 14 | 15 | 17 | 16 | 17 |
| qz | +24 | +30 | +37 | +51 | +41 |
| k | 0.18 | 0.17 | 0.18 | 0.18 | 0.21 |
| mg | 0.53 | 0.54 | 0.49 | 0.52 | 0.53 |

14. Hypersthene andesite flow. Lake level under Llao Rock. Anal. H. N. Stokes. Diller and Patton, *op. cit.*, p. 94.
15. Hypersthene andesite dike. Devil's Backbone. Anal. H. N. Stokes. Diller and Patton, *ibid.*
16. Hypersthene andesite. Rim just south of Watchman. Anal. H. N. Stokes. Diller and Patton, *ibid.*
17. Hornblende andesite. Dry Butte dome, east of Mount Scott. Anal. W. H. Herdsman.
18. Hypersthene andesite. Palisades, under Roundtop. Anal. H. N. Stokes. Diller and Patton, *loc. cit.*

ANALYSES OF DACITE LAVAS AND WELDED TUFF

| | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 68.17 | 68.64 | 70.10 | 70.30 | 70.77 | 71.32 | 71.87 |
| $Al_2O_3$ | 15.60 | 15.62 | 15.18 | 14.52 | 14.83 | 14.70 | 14.53 |
| $Fe_2O_3$ | 2.31 | 1.28 | 1.78 | 0.37 | 1.35 | 1.03 | 1.28 |
| FeO | 0.94 | 2.20 | 1.09 | 2.56 | 1.25 | 1.83 | 1.02 |
| MgO | 1.02 | 1.14 | 0.74 | 0.93 | 0.64 | 0.58 | 0.48 |
| CaO | 2.76 | 3.05 | 2.27 | 2.94 | 2.12 | 2.34 | 1.59 |
| $Na_2O$ | 5.15 | 4.52 | 5.15 | 4.86 | 5.07 | 4.83 | 5.08 |
| $K_2O$ | 2.46 | 2.23 | 2.58 | 2.66 | 2.68 | 2.58 | 2.84 |
| $H_2O+$ | 0.45 | 0.54 | 0.19 | 0.33 | 0.33 | 0.13 | 0.22 |
| $H_2O-$ | 0.09 | 0.26 | 0.10 | 0.14 | 0.07 | 0.13 | 0.06 |
| $TiO_2$ | 0.54 | 0.49 | 0.48 | 0.44 | 0.38 | 0.22 | 0.41 |
| $P_2O_5$ | 0.13 | 0.13 | 0.13 | 0.09 | 0.13 | 0.08 | 0.10 |
| MnO | Trace | Trace | Trace | Trace | Trace | Trace | Trace |
| BaO | 0.06 | ..... | 0.08 | ..... | 0.08 | ..... | 0.08 |
| SrO | 0.03 | ..... | 0.03 | ..... | 0.02 | ..... | 0.03 |
| Cl | Trace | ..... | 0.03 | ..... | 0.11 | ..... | Trace |
| $ZrO_2$ | ..... | ..... | 0.04 | ..... | 0.05 | ..... | 0.04 |
| Totals | 99.71 | 100.10 | 99.97 | 100.14 | 99.88 | 99.77 | 99.63 |
| *Norms* | | | | | | | |
| q | 21.66 | 24.90 | 24.78 | 23.94 | 25.26 | 27.06 | 27.66 |
| or | 15.01 | 13.34 | 15.01 | 15.57 | 16.12 | 15.01 | 16.68 |
| ab | 43.49 | 38.25 | 43.51 | 40.87 | 42.97 | 40.87 | 42.97 |
| an | 11.95 | 14.18 | 10.56 | 10.01 | 9.45 | 10.84 | 7.23 |
| c | ..... | 0.51 | 0.10 | ..... | ..... | ..... | 0.41 |
| wo | 0.35 | ..... | ..... | 1.51 | 0.13 | ..... | ..... |
| en | 2.60 | 2.80 | 1.90 | 2.30 | 1.60 | 1.40 | 1.20 |
| fs | ..... | 2.24 | ..... | 3.83 | 0.53 | 2.11 | 0.13 |
| mt | 1.39 | 1.86 | 2.09 | 0.46 | 2.09 | 1.39 | 1.86 |
| il | 1.06 | 0.91 | 0.91 | 0.76 | 0.76 | 0.46 | 0.76 |
| hm | 1.28 | ..... | 0.32 | ..... | ..... | ..... | ..... |
| ap | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 |
| Normative plagioclase | $Ab_{73}$ | $Ab_{73}$ | $Ab_{81}$ | $Ab_{80}$ | $Ab_{82}$ | $Ab_{79}$ | $Ab_{86}$ |
| *Niggli values* | | | | | | | |
| si | 301 | 301 | 325 | 322 | 340 | 347 | 369 |
| al | 40 | 40 | 42 | 39 | 42 | 42 | 44 |
| fm | 18 | 20 | 16 | 18 | 15 | 15 | 13 |
| c | 13 | 14 | 12 | 14 | 11 | 12 | 9 |
| alk | 29 | 26 | 30 | 29 | 32 | 31 | 34 |
| qz | +85 | +97 | +105 | +106 | +112 | +123 | +133 |
| k | 0.24 | 0.25 | 0.25 | 0.26 | 0.26 | 0.26 | 0.27 |
| mg | 0.38 | 0.37 | 0.33 | 0.37 | 0.31 | 0.27 | 0.29 |

19. Welded dacite tuff (ignimbrite). Wineglass. Anal. H. N. Stokes. Diller and Patton, *op. cit.*, p. 140.
20. Dacite dome, east of Mount Scott. Anal. W. H. Herdsman.
21. Hypersthene dacite. Feeder of Cleetwood flow, at water's edge. Anal. H. N. Stokes. Diller and Patton, *loc. cit.*
22. Glassy dacite. South edge of Grouse Hill dome. Anal. W. H. Herdsman.
23. Hypersthene dacite, vitrophyric type. South edge of Llao flow. Anal. H. N. Stokes. Diller and Patton, *loc. cit.*
24. Tridymite-rich rhyodacite. East wall of Sun Valley, on side of Grayback Ridge. Anal. W. H. Herdsman.
25. Hypersthene dacite dike, probably rich in cristobalite. Below Llao Rock. Anal. H. N. Stokes. Diller and Patton, *loc. cit.*

Analyses of the ejecta of the culminating explosions

| | 26 | 27 | 28 | 29 | 30 | 31 | 32 |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 53.94 | 56.10 | 56.85 | 66.38 | 67.41 | 68.56 | 69.50 |
| $Al_2O_3$ | 19.42 | 18.84 | 18.31 | 15.74 | 15.76 | 14.22 | 15.18 |
| $Fe_2O_3$ | 3.36 | 2.27 | 2.88 | 0.64 | 1.88 | 1.42 | 1.24 |
| FeO | 3.09 | 5.03 | 3.15 | 2.12 | 1.76 | 1.49 | 1.42 |
| MgO | 4.41 | 3.56 | 3.92 | 0.74 | 1.35 | 0.83 | 0.83 |
| CaO | 8.73 | 7.50 | 7.20 | 2.68 | 3.36 | 2.35 | 2.08 |
| $Na_2O$ | 3.71 | 3.86 | 3.89 | 4.11 | 4.54 | 5.18 | 4.78 |
| $K_2O$ | 1.26 | 0.70 | 1.23 | 2.37 | 2.36 | 2.47 | 2.18 |
| $H_2O+$ | 1.10 | 1.10 | 0.95 | 4.00 | 0.54 | 3.32 | 2.51 |
| $H_2O-$ | 0.25 | Nil | 0.16 | 0.50 | 0.09 | | |
| $TiO_2$ | 0.76 | 0.76 | 1.08 | 0.48 | 0.56 | 0.58 | 0.41 |
| $P_2O_5$ | 0.17 | 0.19 | 0.22 | 0.05 | 0.12 | 0.10 | 0.21 |
| MnO | Trace | 0.17 | Trace | Nil | Trace | 0.03 | 0.03 |
| BaO | ..... | ..... | 0.04 | ..... | 0.06 | ..... | ..... |
| Totals | 100.20 | 100.08 | 99.88 | 99.81 | 99.81 | 100.55 | 100.37 |
| | | | *Norms* | | | | |
| q | 4.08 | 7.86 | 9.36 | 25.56 | 22.92 | 23.34 | 27.72 |
| or | 7.23 | 4.45 | 7.23 | 13.90 | 13.90 | 14.46 | 12.79 |
| ab | 31.44 | 32.49 | 33.01 | 34.58 | 38.25 | 44.02 | 40.35 |
| an | 32.53 | 31.97 | 28.63 | 13.34 | 15.57 | 8.06 | 9.45 |
| c | ..... | ..... | ..... | 1.53 | ..... | ..... | 1.53 |
| wo | 4.18 | 1.86 | 2.32 | ..... | 0.12 | 1.16 | ..... |
| en | 11.10 | 8.90 | 9.80 | 1.90 | 3.40 | 2.10 | 2.10 |
| fs | 1.72 | 6.47 | 1.58 | 2.51 | 0.92 | 0.66 | 0.92 |
| mt | 4.87 | 3.25 | 4.18 | 0.93 | 2.55 | 2.09 | 1.86 |
| il | 1.37 | 1.37 | 2.13 | 0.91 | 1.06 | 1.06 | 0.76 |
| ap | 0.34 | 0.34 | 0.67 | 0.17 | 0.34 | 0.34 | 0.34 |
| Normative plagioclase | $Ab_{49}$ | $Ab_{50}$ | $Ab_{54}$ | $Ab_{72}$ | $Ab_{71}$ | $Ab_{85}$ | $Ab_{81}$ |
| | | | *Niggli values* | | | | |
| si | 146 | 162 | 169 | 318 | 283 | 325 | 337 |
| al | 31 | 32 | 32 | 44 | 39 | 40 | 43 |
| fm | 32 | 33 | 32 | 16 | 21 | 17 | 17 |
| c | 25 | 23 | 23 | 14 | 15 | 12 | 11 |
| alk | 12 | 12 | 13 | 26 | 25 | 31 | 29 |
| qz | −2 | +14 | +17 | +114 | +83 | +101 | +121 |
| k | 0.18 | 0.10 | 0.17 | 0.28 | 0.25 | 0.24 | 0.23 |
| mg | 0.56 | 0.46 | 0.54 | 0.33 | 0.41 | 0.35 | 0.37 |

26. Hornblende-rich scoria bomb. *Nuée ardente* deposit in Castle Creek canyon, near Llao's Hallway. Anal. W. H. Herdsman.
27. Scoria bomb. *Nuée ardente* deposit in Sun Creek canyon. Anal. W. H. Herdsman.
28. Hornblende-rich scoria bomb. Top of Llao Rock. Anal. H. N. Stokes. Diller and Patton, *op. cit.*, p. 140.
29. Dacite lump pumice. *Nuée ardente* deposit in Sun Creek canyon. Anal. W. H. Herdsman.
30. Light-colored "secretion" found among ejecta on divide between Sand and Annie creeks, near south rim of caldera. Includes 0.02 per cent S. Anal. H. N. Stokes. Diller and Patton, *loc. cit.*
31. Dacite lump pumice. Pumice fall (?) near Chemult. Anal. J. J. Fahey, U. S. Geol. Surv. Bull. 875, p. 159, 1937.
32. Dacite lump pumice. From *nuée ardente* deposits near Lonroth (Beaver Marsh). Anal. J. J. Fahey, *ibid.*

## Petrology

The rocks of the Crater Lake region, like those of all the High Cascade volcanoes studied thus far, belong to the calcic igneous series as defined by Peacock.[8] The alkali-lime index, that is, the silica percentage at which the content of lime equals that of the alkalis combined, is approximately 62 (see figure 32). For the lavas of the Lassen region, the index is 63.9; for those of Mount Shasta, 63.7; and for those of Mount St. Helens, 63.2.

According to the scheme proposed by Niggli,[9] the magma types of the Crater Lake region are mainly quartz dioritic (peleitic), dioritic, and trondhjemitic. Burri,[10] who was struck by the resemblance of the Crater Lake rocks to the Tertiary lavas of the Sierra Nevada, grouped them together as the Sierra Nevada (effusive) type of the Pacific Province. However, the Crater Lake lavas are more similar in many respects to those of the Lassen region than they are to the effusive rocks of the Sierras. Thus, the values for $al$ in the Crater Lake series are consistently closer to those of the Lassen lavas. So are the values for $alk$ and $al\text{-}alk$ among the basic lavas ($si<200$). The values for $c$ in the Crater Lake rocks, on the other hand, are closer to those of the Sierran lavas.

The principal differences between the Lassen and Crater Lake series have already been shown in an earlier paper.[11] Briefly, they are as follows: lime is consistently higher among the Lassen rocks; potash is also higher except among lavas with less than 56 per cent $SiO_2$; soda is distinctly higher among the rocks of Crater Lake; so is iron, except in the most basic flows; and finally, magnesia is higher among the basic lavas of Crater Lake, but lower among lavas with more than 55 per cent $SiO_2$. Noteworthy is the wider range in silica content of the Lassen series.

Among the acid rocks of the Lassen region ($si>300$) the $k$ value, that is, the molecular ratio of $K_2O$ to total alkalis, may reach as high as 0.5, though in the Crater Lake series the $k$ value never exceeds 0.28 (see figure 33). This low potash content of the Crater Lake lavas is reflected in the absence of orthoclase and the extreme rarity of biotite in even the most siliceous types. The acid dacites of the Lassen country, on the contrary, contain biotite in abundance. The acid effusive rocks and the Mesozoic intrusives of the Sierra Nevada also show high $k$ values, the magma types tending toward the granodioritic. If assimilation has played any role in the differentiation of the Lassen magmas, their high $k$ values may imply contamination with rocks of the granodiorite basement. Presumably the upper parts of the magma chambers beneath the Crater Lake region lay far above such a basement and among the thick series of calc-alkaline lavas which outcrop in the Western Cascades. Causes other than assimilation, however, may well account for the observed differences.

In their low $k$ values, the Crater Lake lavas resemble those of Mounts Shasta and St. Helens. They are not, however, so poor in potash as the lavas of Montserrat.[12] Nevertheless there are strong similarities between the Crater Lake rocks and those of the Lesser Antilles in general.

In brief, the Mazama and pre-Mazama flows of the Crater Lake region belong to the same calcic magma type as those of Lassen Peak and the Lesser Antilles, though exhibiting many similarities to the Tertiary lavas of the Sierra Nevada. That they also bear a notable resemblance to the Mesozoic batholithic rocks of the Sierra Nevada suggests the persistence, over a very long period and with little modification, of similar magmas beneath the Sierra Nevada–Cascade orogenic belt.

We may now inquire concerning the Eocene-Miocene rocks of the Western Cascades and the igneous rock series in the region east of the High Cascades. Thayer[13] has shown that, compared with the rocks of the Western Cascades, the Pliocene and younger rocks of the High Cascades are richer in $Al_2O_3$ in the range above 53.5 per cent $SiO_2$, in lime above 55 per cent $SiO_2$, and in $Na_2O$ above 65 per cent and below 56 per

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[8] M. A. Peacock, "Classification of igneous rock series," Jour. Geol., vol. 39, pp. 54–67, 1931.

[9] Paul Niggli, "Die Magmentypen," Schweiz. mineral. u. petrol. Mitteil., vol. 16, pp. 335–400, 1936.

[10] C. R. Burri, "Chemismus und provinziale Verhältnisse der jungeruptiven Gesteine des pazifischen Ozeans und seiner Umrandung," Schweiz. mineral. u. petrogr. Mitteil., vol. 6, pp. 143–146 and fig. 33, 1926.

[11] Howel Williams, "Newberry volcano of central Oregon," Bull. Geol. Soc. Amer., vol. 46, p. 296, 1935.

[12] A. G. MacGregor, "The volcanic history and petrology of Montserrat," Philos. Trans. Roy. Soc. London, ser. B, no. 557, vol. 229, pp. 1–90, 1938.

[13] T. P. Thayer, *op. cit.*, pp. 1646–1647.

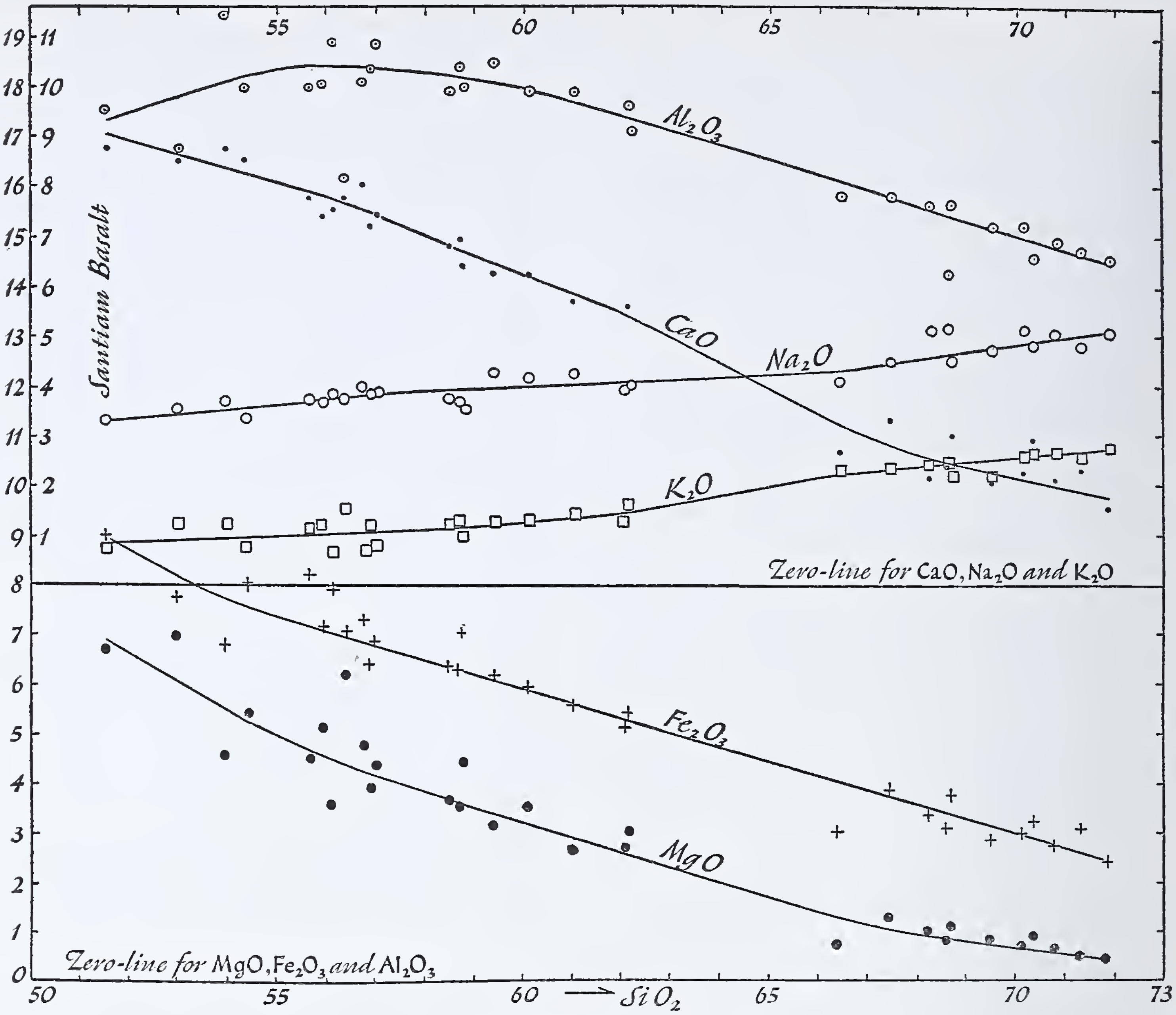

Fig. 32. Variation diagram of the Crater Lake rocks

cent $SiO_2$, and are generally richer in magnesia. The Western Cascade lavas are consistently richer in iron oxide and potash. From the available evidence, it is clear that the Western Cascade lavas belong to the calc-alkaline series, for the alkali-lime index is 58.6. Since the High Cascade lavas are generally richer in alumina, lime, soda, and magnesia and poorer in potash and iron, it is possible that they were derived by crystal differentiation of a magma common to both, for the settling of early-formed feldspars and magnesian minerals would readily account for the differences. Certainly a sharp break seems to have occurred in the magmatic history of the Cascade volcanoes at the close of the Miocene, and perhaps this sudden change was related causally to the strong orogenic disturbances which took place at that time.

To the east, on the other hand, in the Medicine Lake Highlands of northern California, and at the Newberry volcano of central Oregon, calc-alkaline magmas were being erupted simultaneously with the calcic magmas of the High Cascades.

Throughout the High Cascades, at least in Oregon, the dominant lavas are either olivine basalts or olivine-bearing basaltic andesites such as those which immediately underlie Mount Mazama and form the bulk of the volcanoes to the south. Indeed, scarcely any other type of lava was erupted in the High Cascades during Pliocene times. Subsequently, at certain centers on and near the crest of the range, differentiation led to the eruption of hypersthene andesite and of more acid types. At these centers, large composite cones, including Shasta, Mazama, Hood, Adams, Rainier, and Baker, were built. Yet even while these were active, olivine basalts and basaltic andesites continued to escape from neighboring vents. Thayer has noted a similar relationship in the vicinity of Mount Jefferson:

> The occurrence of large andesitic cones literally in the midst of small basaltic cones suggests that the more acidic lavas were erupted from comparatively small pockets or cupolas in the main magma chamber. The localization of differentiation may have been due to local cooling, shown by the porphyritic nature of the andesites and associated basalts in the high peaks as compared to the uniformly fine-grained textures in the basalts of the smaller cones.[14]

The activity of Mount Mazama itself began, as we have seen, with the eruption of hypersthene andesite, and during most of its history the volcano erupted no other type of magma. At the northern end of the Cascade Range, on Mounts Rainier and Baker, this is the only type of magma represented. Southward, however, the variety of magmas erupted by the major cones of the High Cascades shows an almost regular increase. This southward increase in the diversity of the products of the Pleistocene and younger cones of the High Cascades has been emphasized repeatedly since it was first detected by Hague and Iddings. Its cause remains unknown.

The hypersthene andesites of Mount Mazama, like those of the circum-Pacific volcanoes in general, are characterized by an abundance of porphyritic feldspar. In this respect they contrast strongly with most of the pre-Mazama basalts and basaltic andesites. This difference implies more advanced crystallization of the hypersthene andesite magma prior to eruption, and helps to explain why it was more explosive than the earlier, more basic magmas.

Hornblende andesite lavas are rare throughout the High Cascades. In the Crater Lake region, only two examples are known. Between Mount Mazama and Mount Shasta, only one occurrence is known, namely in the dome on the summit of Rustler Peak. On Mount Shasta, hornblende andesite is best developed in the dome of Black Butte. On Mount St. Helens, the plugs (domes) invariably carry hornblende. In brief, hornblende andesite lava is almost confined to quickly chilled viscous domes erupted from parasitic vents.

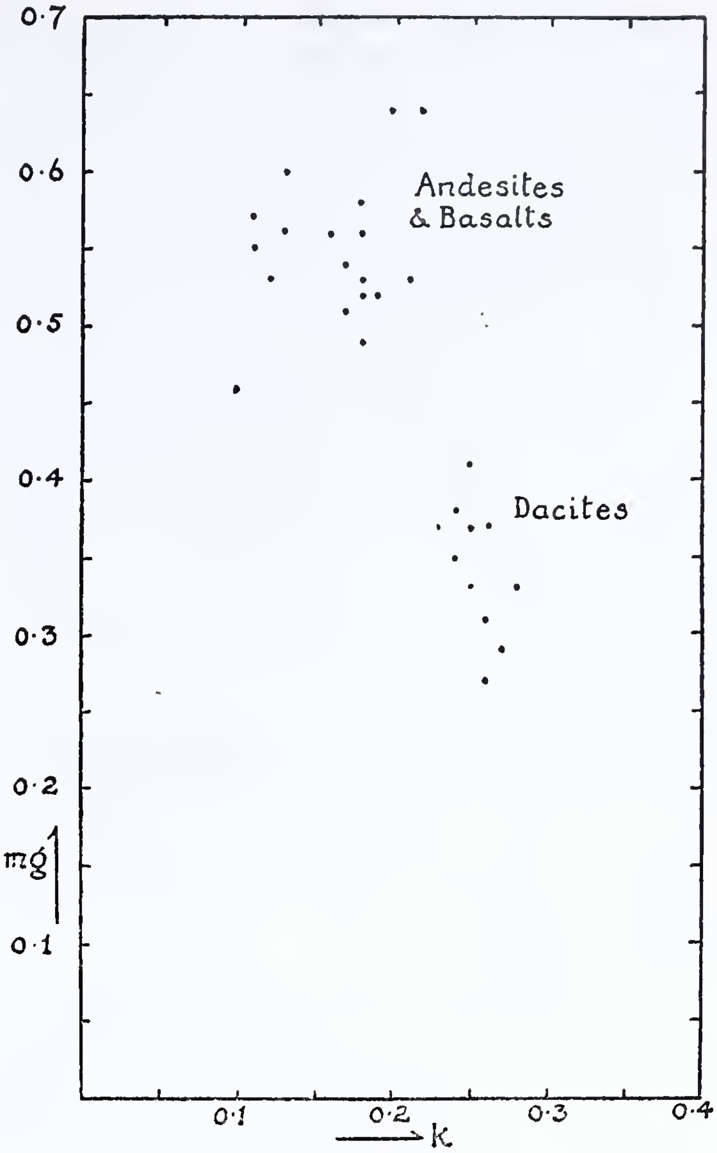

FIG. 33. *K-mg* diagram for the Crater Lake series

On the other hand, hornblende is extremely abundant in the basic scoria flows of Mount Mazama. It is also common in the dacite pumice and almost ubiquitous, though in small amount, among the glassy dacite domes and flows erupted from the Northern Arc of Vents. Yet among the holocrystalline, pilotaxitic dacites of Mazama, the mineral is scarcely ever present. Hence, rapid cooling appears to be necessary to prevent complete resorption of the mineral in magmas of shallow origin.

After the main cone of Mazama had been constructed by long-continued emission of hypersthene andesite, the magma changed to dacite on the one hand and to olivine-bearing basaltic andesite and olivine basalt on the other. Before the culminating eruptions which led to the formation of the caldera, the basic magma escaped from parasitic cinder cones far down the sides of the mountain, and the acid magma was also erupted in the main from parasitic vents, either in the form of viscous flows and domes or as pumice.

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[14] *Ibid.*, p. 1645.

The culminating eruptions were likewise characterized by the presence of opposed types of magma, but now they escaped from the summit vents instead of from fissures on the flanks of the cone. The acid magma was erupted as dacite pumice, essentially like the lavas erupted from the Northern Arc of Vents, but somewhat richer in hornblende. On the other hand, the basic magma was blown out in the form of scoria exceptionally rich in hornblende and basic feldspar and relatively poor in pyroxene and olivine. Yet despite the abundance of hornblende in the products of these final scoria eruptions, the chemical character of the magma is almost identical with that of the hornblende-free parasitic cinder cones and the Pliocene, pre-Mazama lavas.

From a petrological standpoint there is perhaps no more striking feature of the Crater Lake rocks than this extraordinary abundance of hornblende in the basic scoria of the culminating eruptions and the paucity of the mineral among all the earlier products of the volcano. Apparently before the culminating eruptions began, the upper part of the magma chamber was composed of dacite in which the stable ferromagnesian minerals were mainly hypersthene and augite. In this part, hornblende was rare. At greater depth, the reverse was the case.

At Montserrat, MacGregor was led to the conclusion that "the pumiceous and most glassy rocks characterized by green hornblende . . . represent highly gas-charged magma that initiated great volcanic explosions." He pictured this magma as overlain by semiconsolidated material in which the hornblende was brown. This was incapable of initiating great explosions. He suggested further that the pyroxene lavas represent hornblendic magma in which the amphibole has been completely or almost completely altered. Finally, he noted that in general the hornblende of the basic autoliths is brown and more or less resorbed, and he therefore supposed that they were derived from the semiconsolidated upper part of the magma chambers and were blown out with the green hornblende-bearing pumice rising from greater depth.

To what extent are these deductions applicable at Crater Lake? In several respects there appear to be close analogies. In the first place, as we have seen, the hornblende-rich scoria of the culminating eruptions is chemically almost identical with the olivine-bearing basaltic andesites erupted by the parasitic cinder cones. From the distribution of these cinder cones, it may be supposed that they were fed from fissures connected with the main reservoir. Perhaps small satellitic chambers underlay each one. In such shallow chambers, the hornblende which had been stable at greater depths in the principal chamber may have suffered complete breakdown to pyroxene and olivine.

In the second place, it should be noted that in the basic inclusions hornblende is rare and largely replaced by granular pyroxene and ore. Resorbed crystals of oxyhornblende are also typical of the basic inclusions in the dacites of the Lassen region. By far the commonest type of inclusion in the Mazama lavas consists of a crisscross felt of hypersthene and labradorite crystals with accessory augite, a little glass, and either tridymite or cristobalite. Hornblendic inclusions are unknown in hornblende-free lavas. Similarly, the hornblende-rich dacites which form the main dome of Lassen Peak are crowded with basic inclusions characterized by abundant resorbed hornblende, whereas the 1915 lava of Lassen Peak, which presumably rose from very shallow depth, is almost devoid of hornblende and such as there is shows extensive resorption. Further, the basic inclusions in the 1915 lava, which came from still shallower depths and presumably represent fragments of the semiconsolidated roof of the chamber and walls of the conduit, are quite devoid of hornblende. These occurrences lead us to agree with MacGregor's view that close to the surface hornblende breaks down unless the magma is drastically and suddenly chilled. The occurrence of plentiful tridymite or cristobalite, or both, in the basic inclusions is also in accord with the idea of a shallow origin, for siliceous vapors would normally be concentrated at the roof of the magma chamber and in the overlying conduit.

A further analogy may be drawn with the magmas of Montserrat, for at Crater Lake also the explosive magma of the final eruptions was characterized by paucity of any but fresh, green hornblende.

When the climactic eruptions began, the magma in the upper part of the chamber was of dacitic composition and the ratio of crystals to melt was approximately 3 to 7. What little hornblende floated in the magma was still in a stable condition. Below this acid fraction lay more basic magma, of the composition of basaltic andesite, which had crystallized to an even greater extent. At these depths, hornblende was by far the dominant ferromagnesian constituent. Between these two types of magma there was little or no material of intermediate composition. Intermediate magma, hypersthene andesite, like that which had built the main cone of Mazama, was either absent altogether or present in such small amount that it has not been recognized among the ejecta. What agencies brought about such a clear differentiation is not understood. Yet they must have operated earlier, for the basic inclusions in the dacite flows erupted from the Northern Arc of Vents have approximately the same composition as the hornblende-rich scoria. This implies that the semicrystallized roof of the dacite magma chambers had virtually the same composition as the hornblende-rich scoria. Olivine-bearing basaltic andesite, erupted from parasitic cinder cones, basic inclusions in the andesite and dacite flows, and the hornblende-rich scoria of the culminating eruptions are therefore merely heteromorphs.

After the summit of Mount Mazama disappeared, new eruptions took place on the floor of the caldera. Unfortunately, only the products of the youngest of these are visible for inspection. Nothing can therefore be said of the trend of post-caldera differentiation. The visible products on Wizard Island consist of hypersthene andesite. Thus, as its final act, the volcano reverted to eruption of an intermediate type of magma essentially identical with that which had characterized its growth from the beginning until the time it reached maturity.

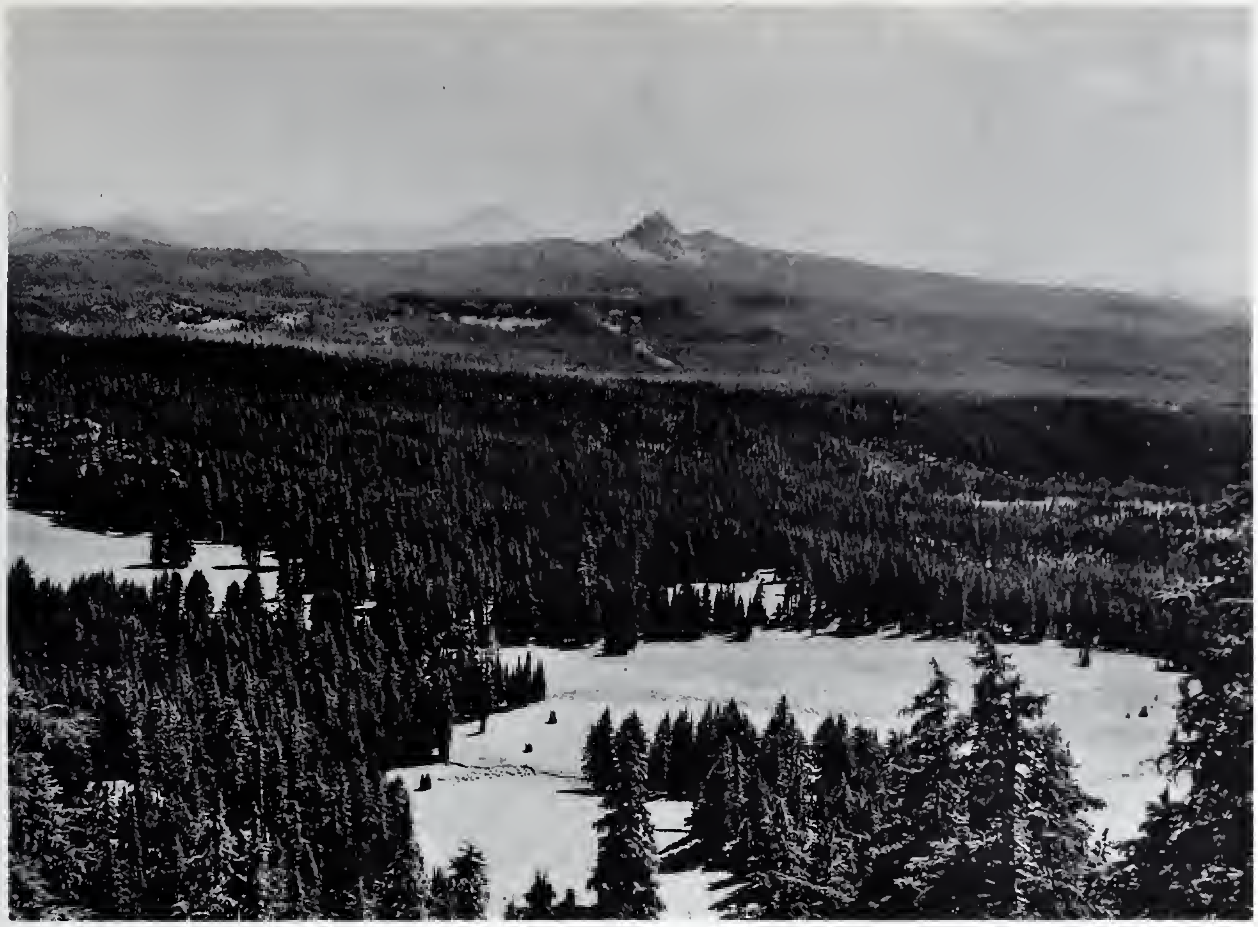


Fig. 1. The Union Peak volcano, looking south from the Rim Road near the Watchman. The long, gentle slopes of the volcano are of lava; the summit pinnacle represents the filling of the central conduit. Between the gentle lava slopes and the central plug, and largely concealed by talus, are the eroded remnants of a tuff cone that formerly occupied the crater. Mount McLoughlin, another High Cascade cone, shows faintly in the distance. The foreground is part of Mount Mazama.

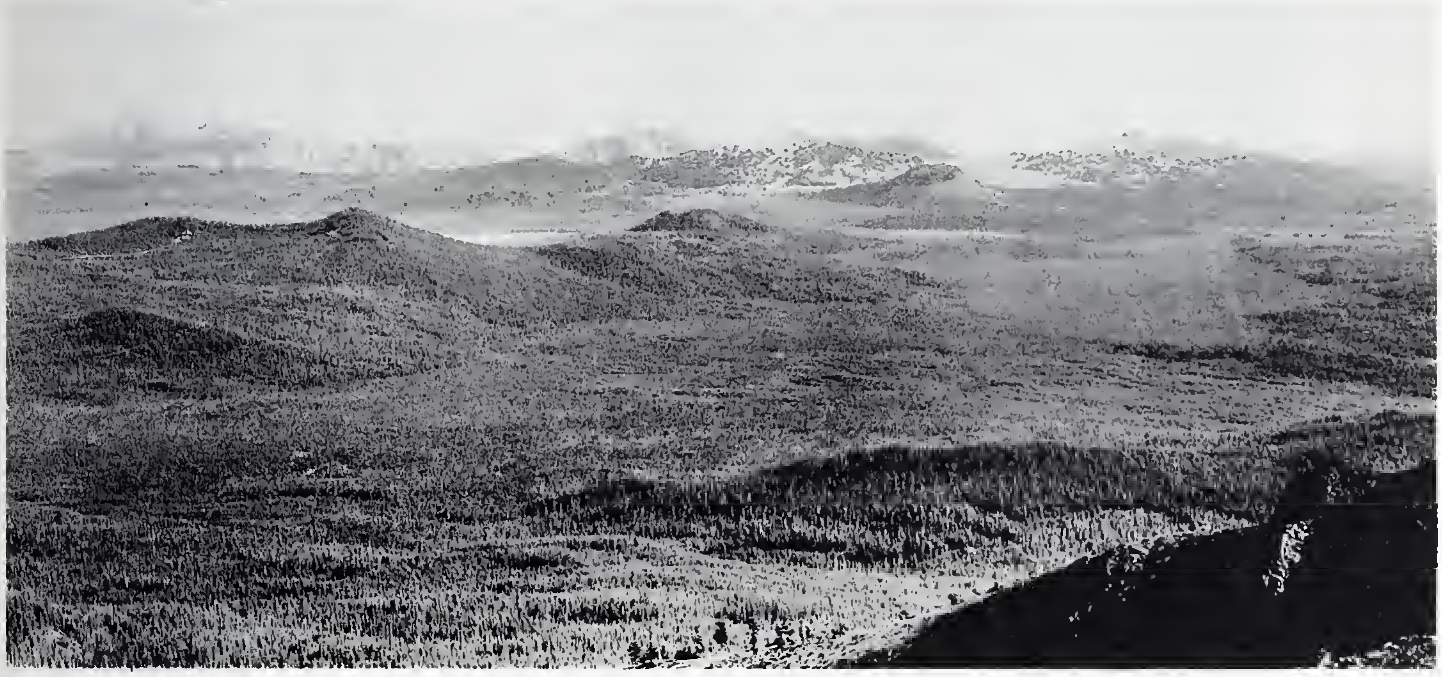


Fig. 2. Looking south from Mount Bailey to the rim of Crater Lake. The wooded hill in the left middle distance is Desert Ridge, composed of pre-Mazama lavas. To the south (right) rise Desert and Red cones, two parasitic scoria cones on the flank of Mount Mazama. Beyond Red Cone, leading up to the caldera rim, is a bare slope of pumice. Almost all the low, wooded country is blanketed with deposits of pumice and scoria flows from Mount Mazama. (Photograph by Victor Duran.)

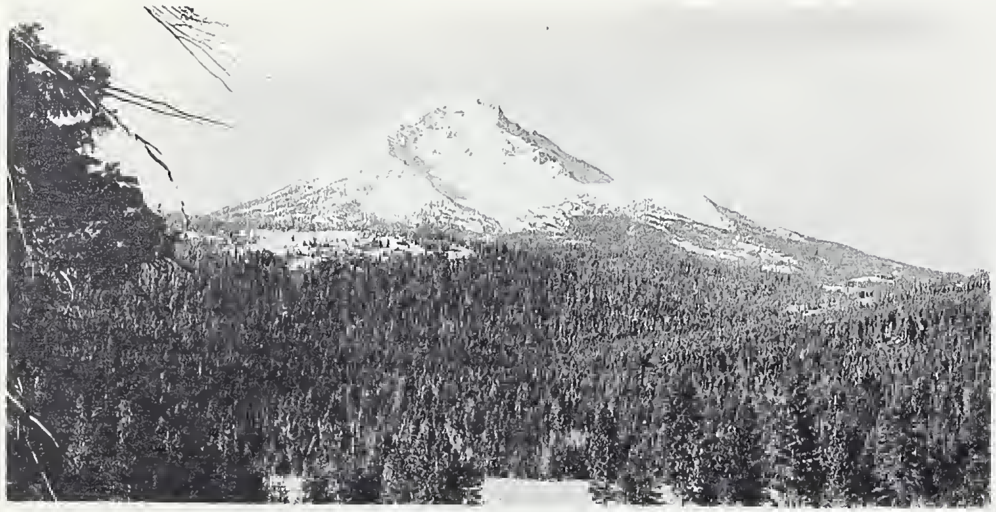


Fig. 1. Mount McLoughlin from the north. The vent of the volcano lies near the head of the glacial cirque, below the summit of the peak. (Photograph by H. B. Taylor.)

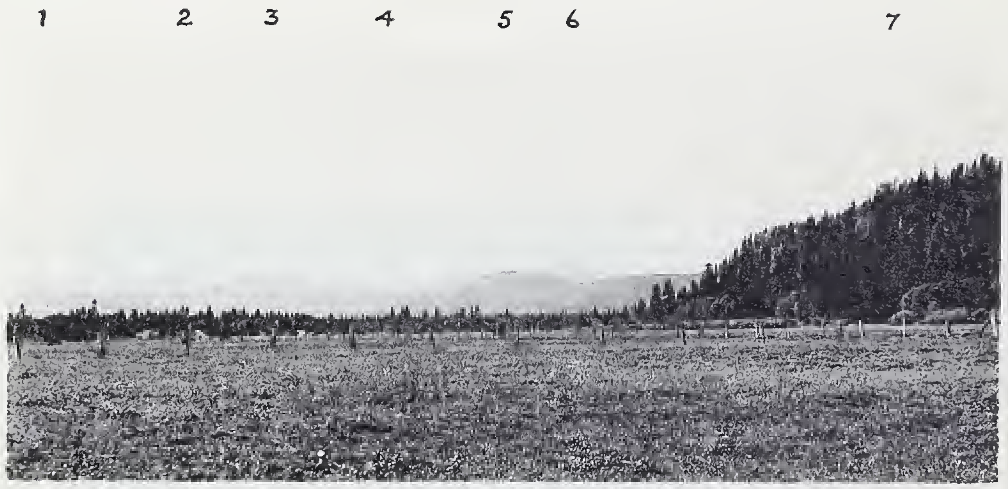


Fig. 2. Looking north toward Crater Lake from near Fort Klamath. Valley floor covered by outwash from the Annie Creek pumice flow. In the distance are: 1, Crater Peak, a parasitic cinder cone; 2, Applegate Peak; 3, Dutton Cliff; 4, Cloudcap (peaks 2, 3, and 4 lie on the rim of Crater Lake); 5, Grayback Ridge; 6, Mount Scott; 7, fault scarp in pre-Mazama, Pliocene olivine basalts.

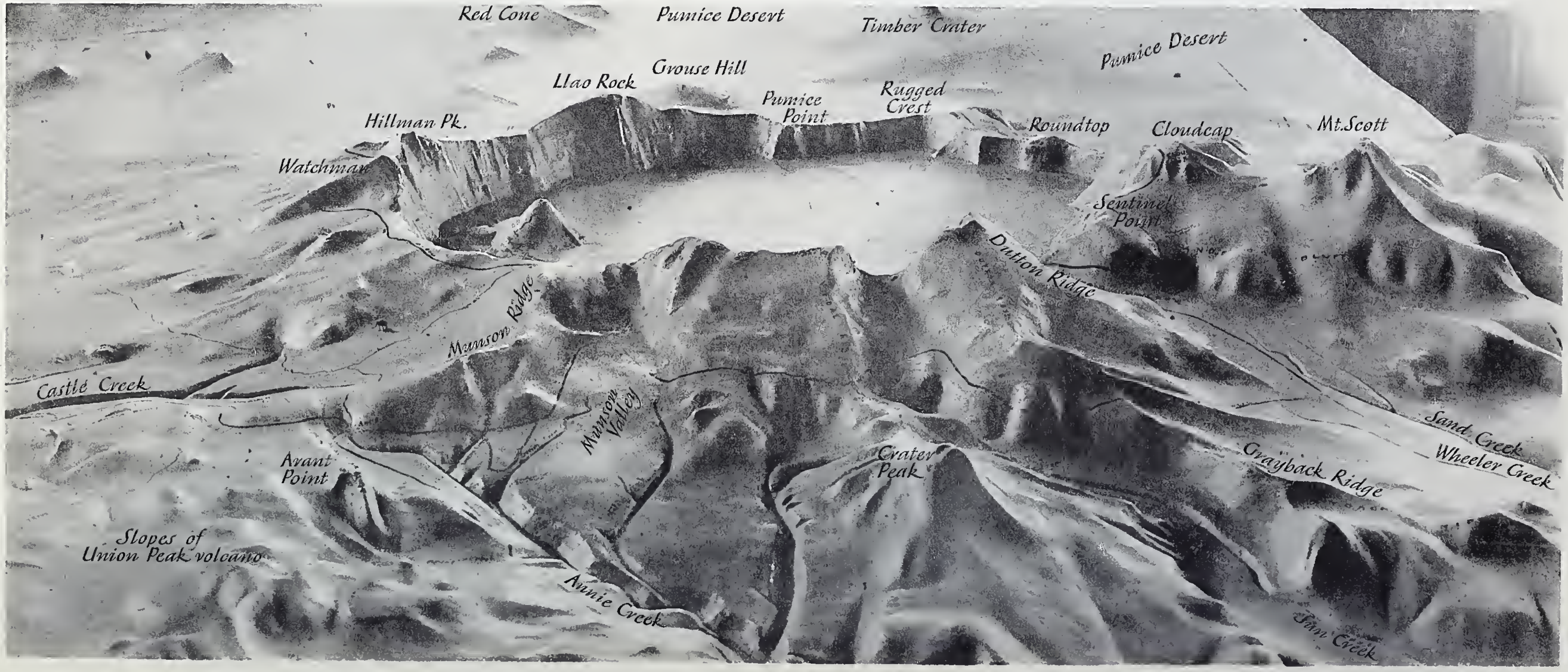
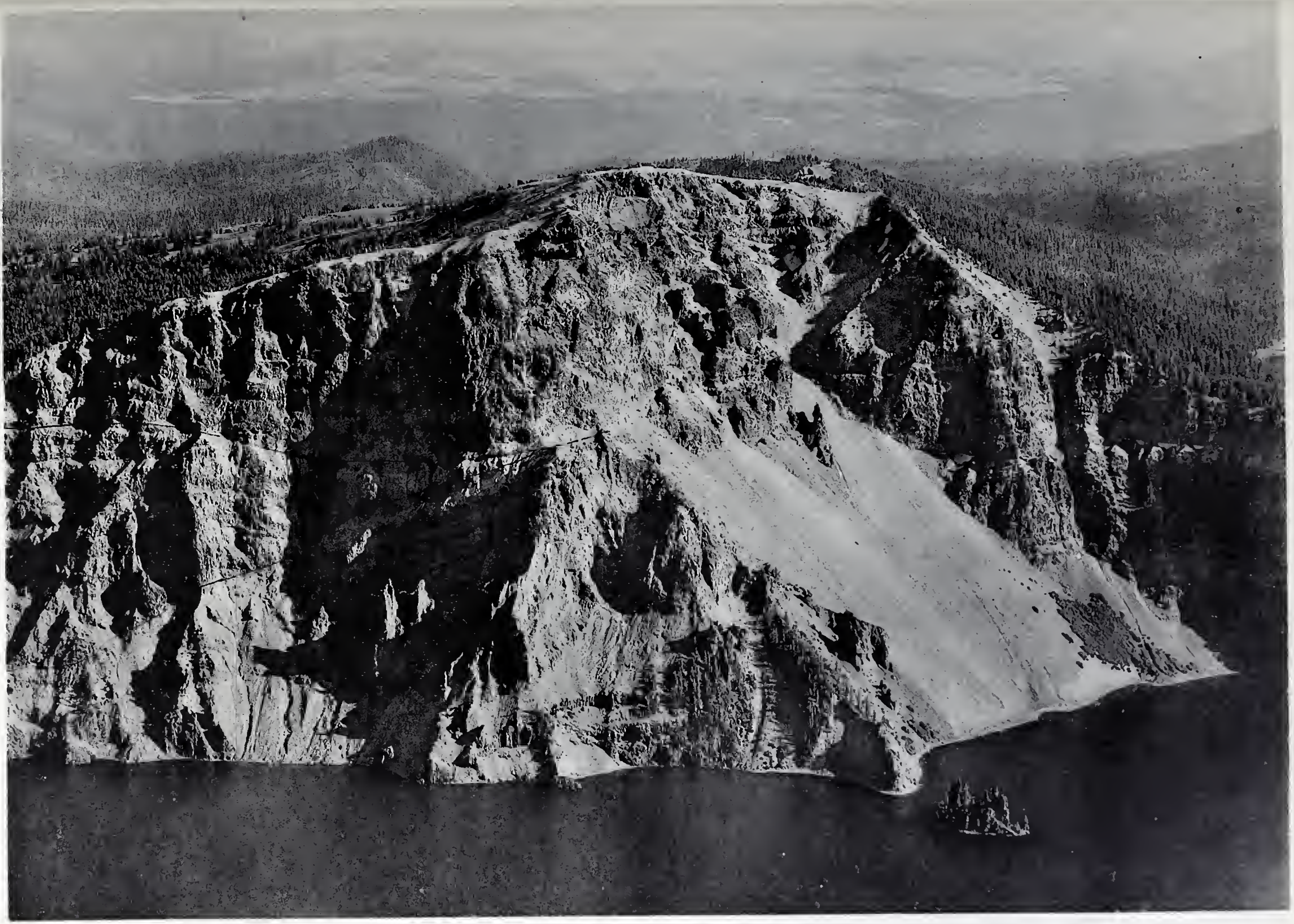


Fig. 3. Model of Crater Lake, showing the physiographic relations between the main peaks and valleys. Note the large glacial canyons on the south (nearer) wall of the caldera; also the diminution in height of the caldera wall toward the northeast, near Roundtop. Vertical scale about twice horizontal.



Dutton Cliff and Phantom Ship. The triangular cliff in the center of the picture is the filling of a vent, possibly the oldest on Mount Mazama. From this, the Phantom Cone was built, of which Phantom Ship is part. The lakeward dips of the lavas and breccias of this cone are clearly shown. After extinction, the Phantom Cone was eroded and then buried by flows from the main vents of Mount Mazama. Note unconformity on the east (left) side between the Phantom and Mazama lavas. A second unconformity, among the Mazama flows, appears higher up the cliff. Thin glacial deposits occur at this horizon, and water seeps issue from them. (Photograph by U. S. Army Air Corps.)

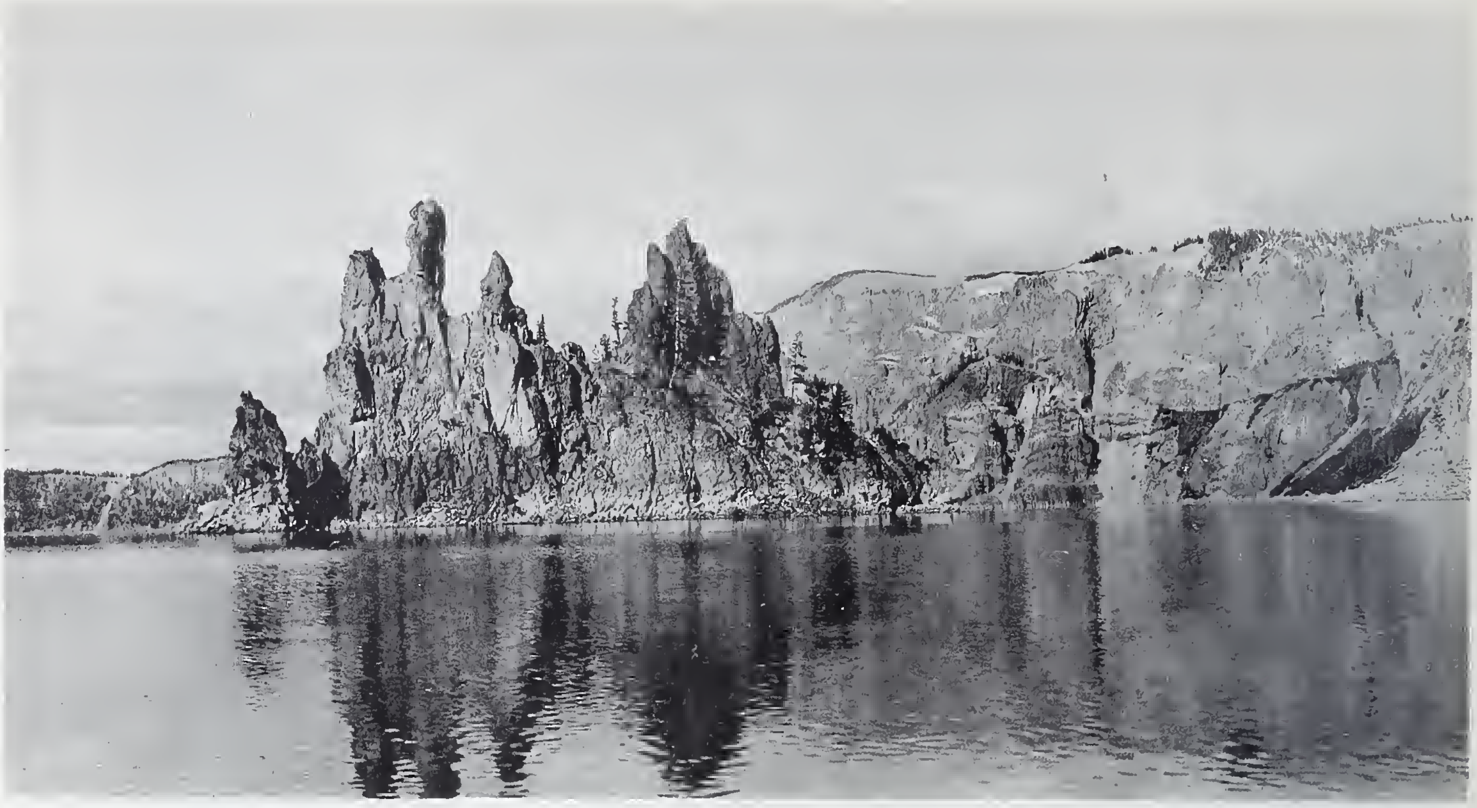


Fig. 1. Phantom Ship, an islet in the lake, composed of tuff breccia cut by vertical, branching dikes, distinguishable by their dark color. Of the five "sails," the ones at each end and the low one in the middle are parts of dikes. So is the dark band at the base of the other two "sails." (Photograph by H. B. Taylor.)

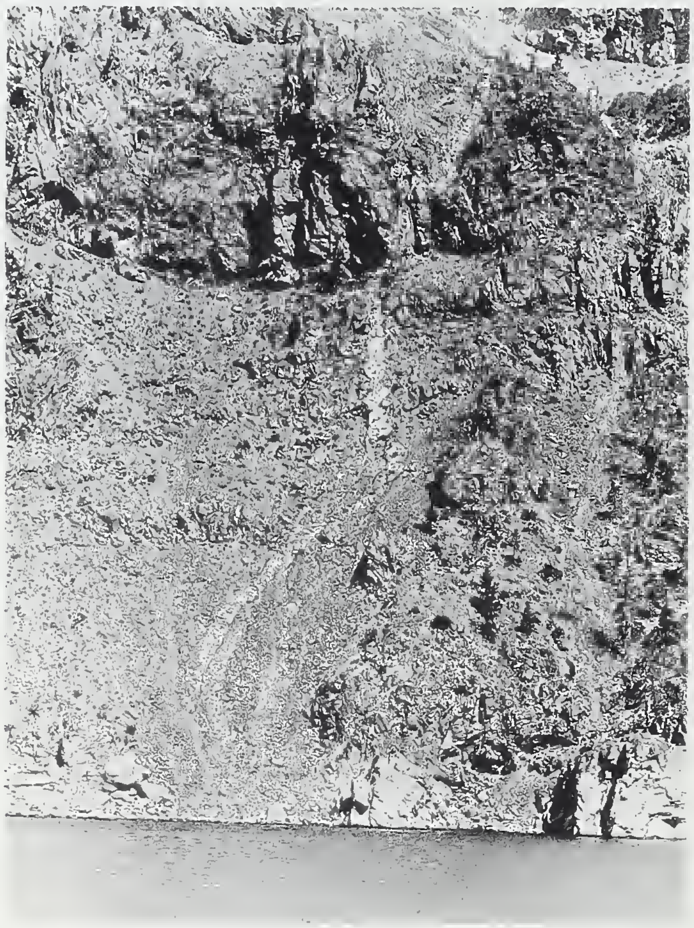
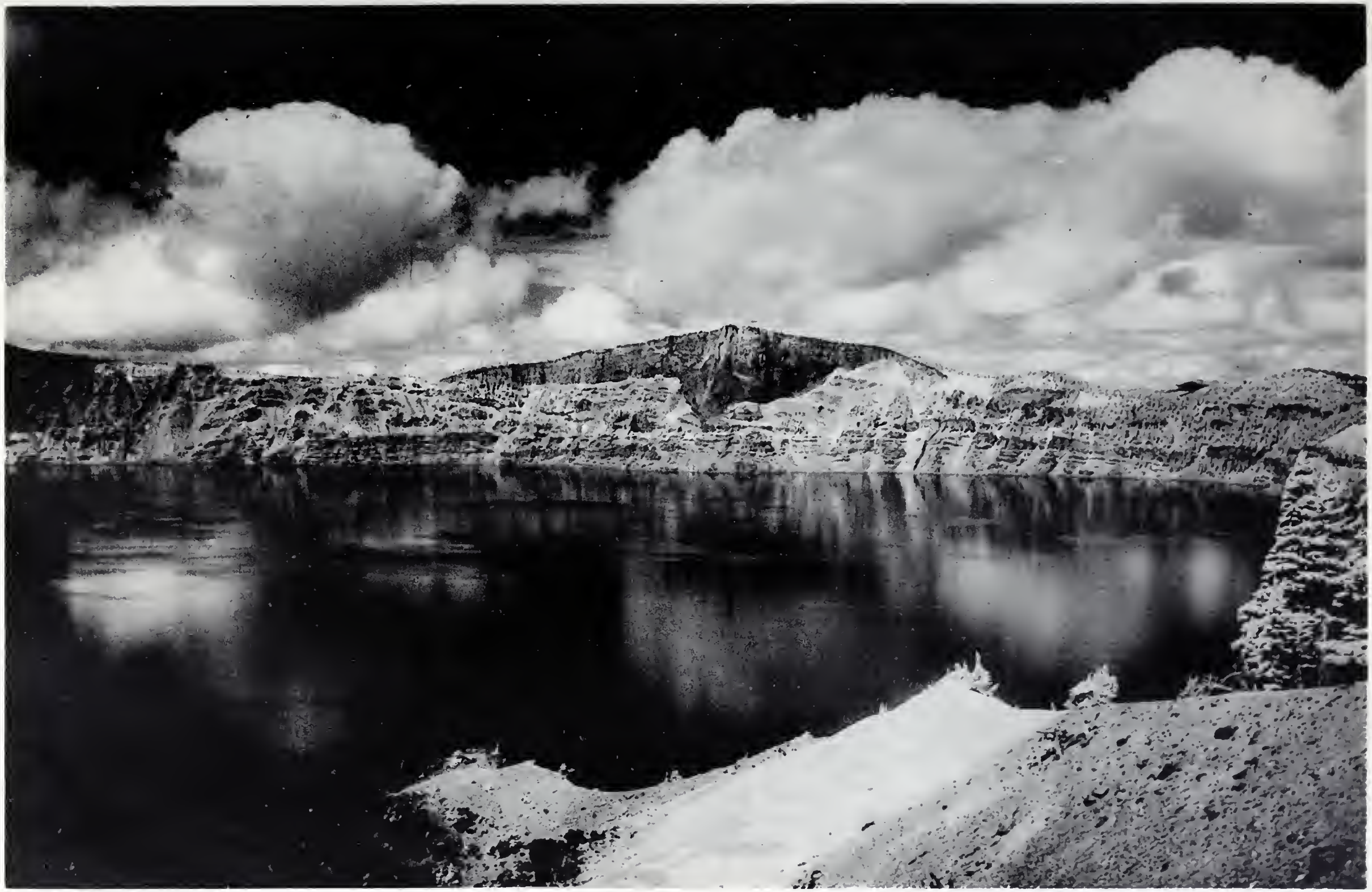


Fig. 2. Dacite dike on the caldera wall beneath Llao Rock. (Photograph by George Grant, National Park Service.)



The west wall of Crater Lake, showing, in addition to the thick dacite flow of Llao Rock, the underlying overlapping arches of lava referred to in the text. (Photograph by William Schoeb.)

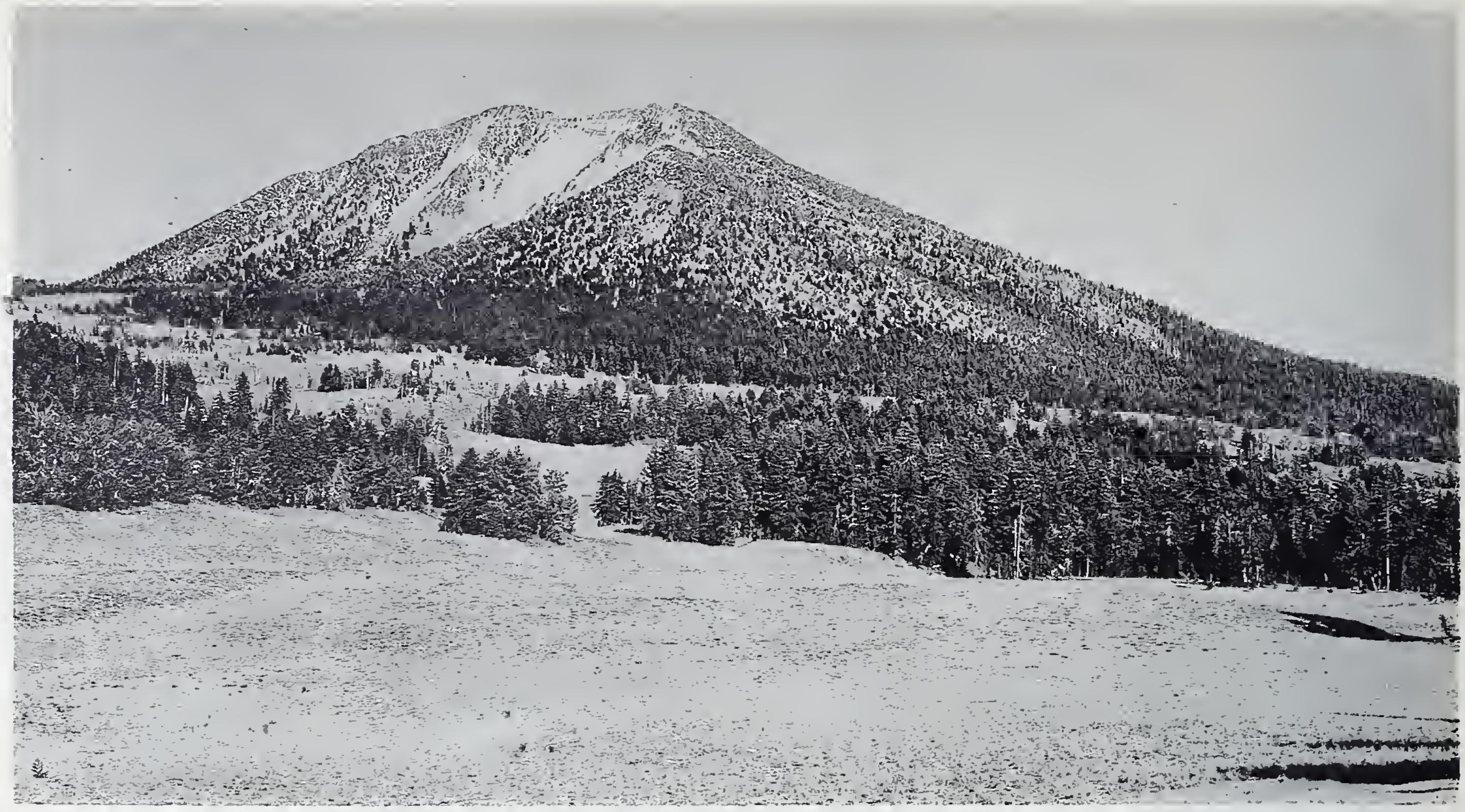


Fig. 1. Mount Scott from the west, showing the cirque on its northwest side. The vent is concealed beneath talus close to the head of the cirque. The foreground is thickly covered by pumice erupted during the culminating activity of Mount Mazama. (Photograph by George Grant, National Park Service.)

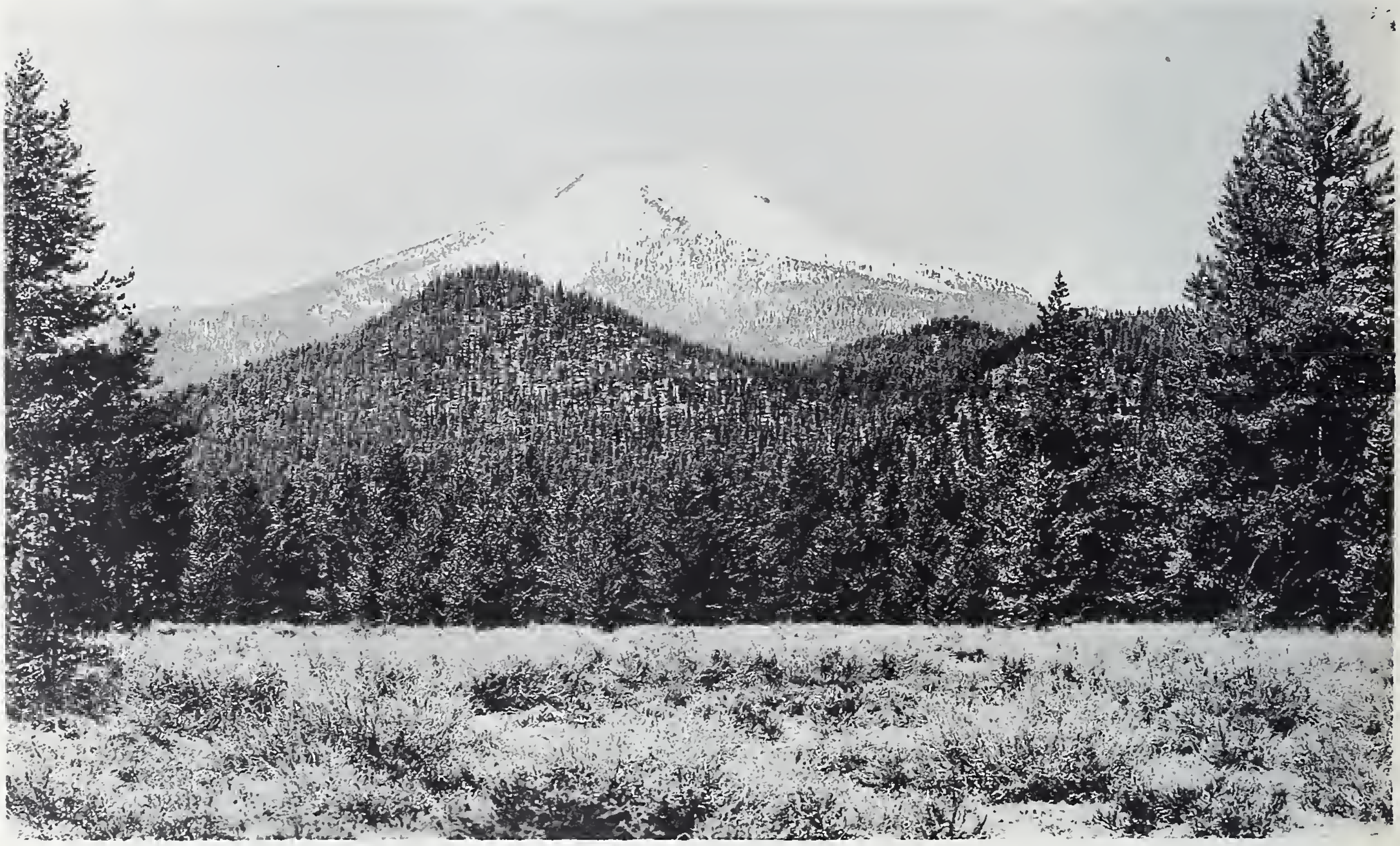
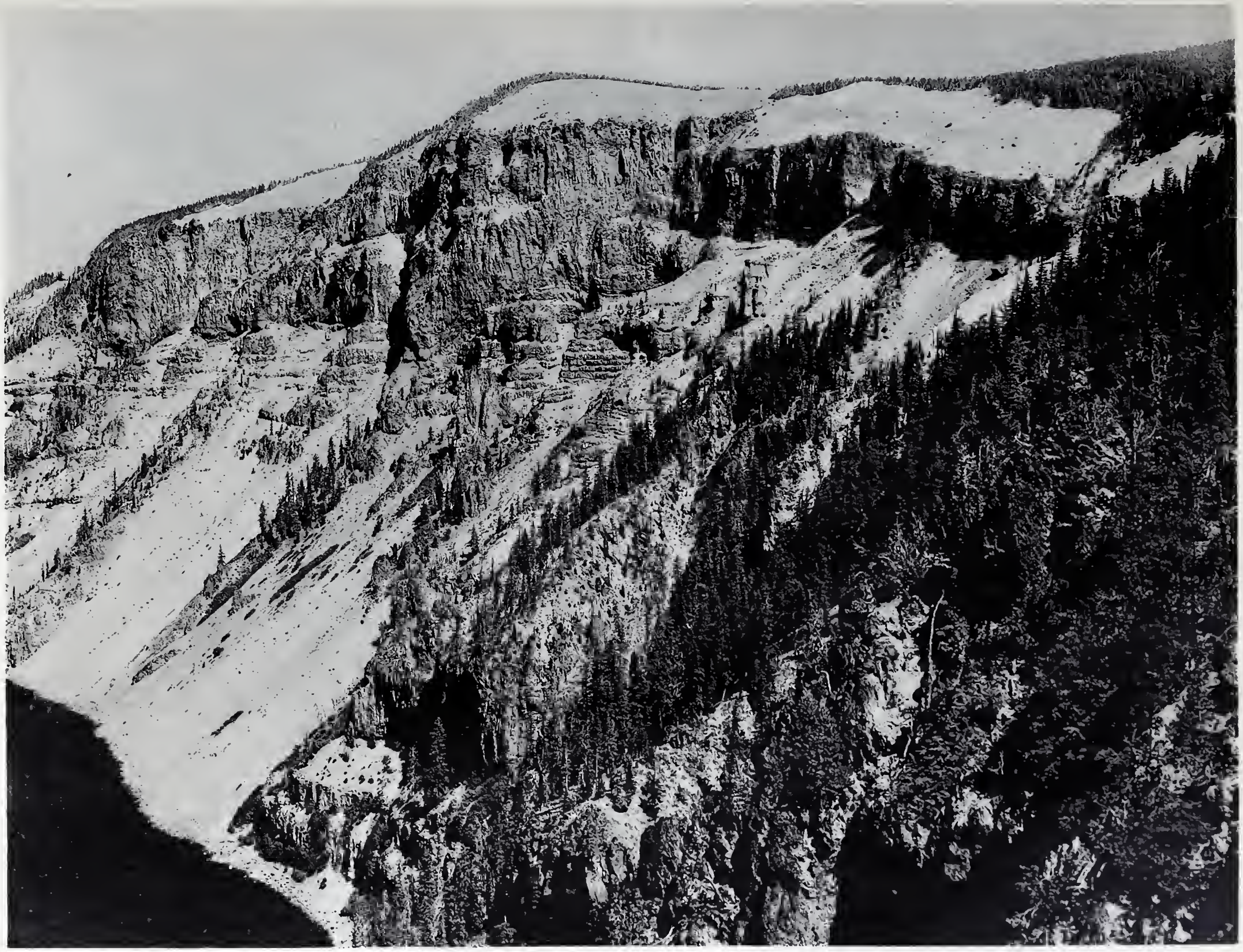


Fig. 2. Mount Scott and parasitic domes, looking west from the Dalles-California highway. From no other angle does the cone of Scott appear so symmetrical (compare figure 1, above). The wooded hills in the middle distance are younger dacite domes. (Photograph by H. B. Taylor.)



Redcloud Cliff, showing the great dacite flow overlain by: 1, pumice; 2, glacial till; 3, pumice; and underlain by an older dacite flow (upper right). Beneath the latter lie thick deposits of pumice and welded tuff, and then a succession of andesite flows. Three distinct glacial layers can be seen within 100 feet of the lake. Two thin layers of lava separate them. Two other glacial layers occur on these walls, but do not show well in the photograph. See, for comparison, panorama, plate 23. (Photograph by George Grant, National Park Service.)

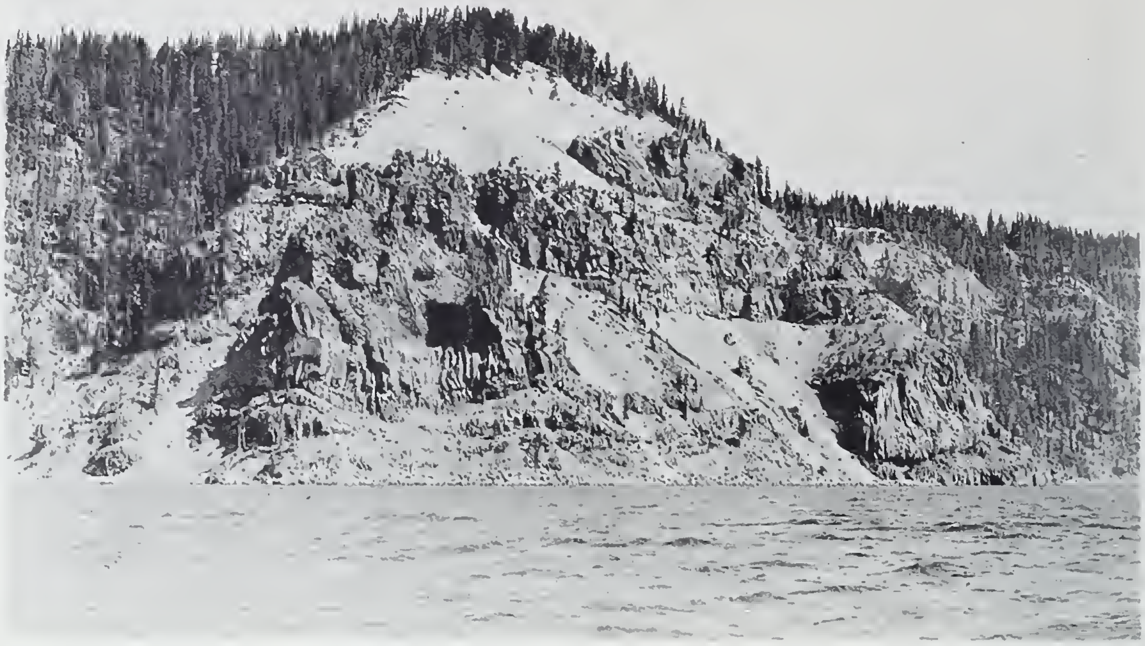


Fig. 1. Pumice Point, north wall of the caldera. A thick pile of dacite pumice resting on andesitic flows and breccia. For position of glacial layers, see figure 8*c*. (Photograph by George Grant, National Park Service.)

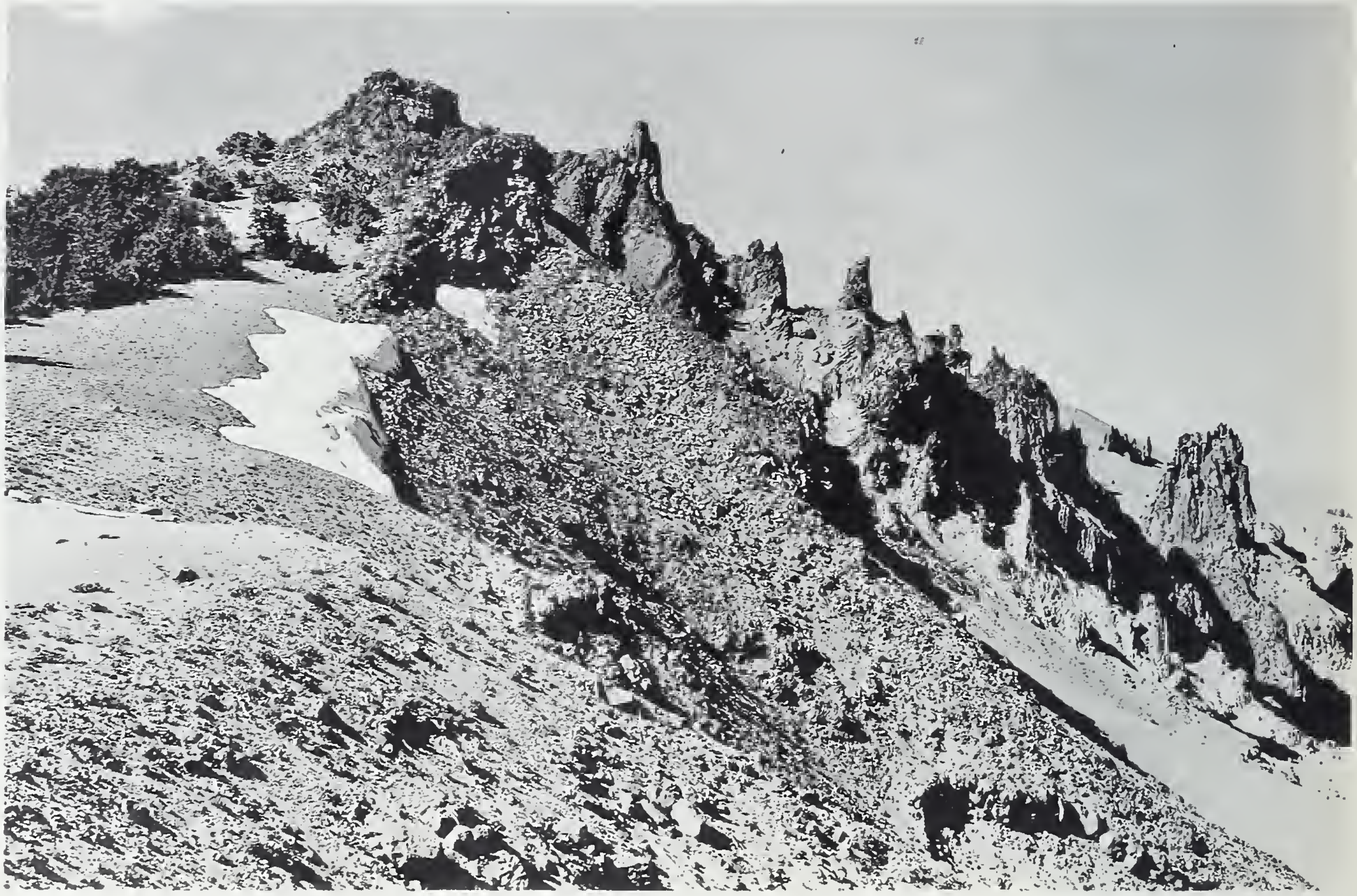


Fig. 2. Hillman Peak from the south. The spires on the caldera wall consist chiefly of cinders and agglomerate; the summit consists of andesite flows. The vent filling of the former Hillman Cone lies among the crags about halfway down the visible part of the caldera wall, and is mainly in shadow. (Photograph by Elmer Aldrich.)

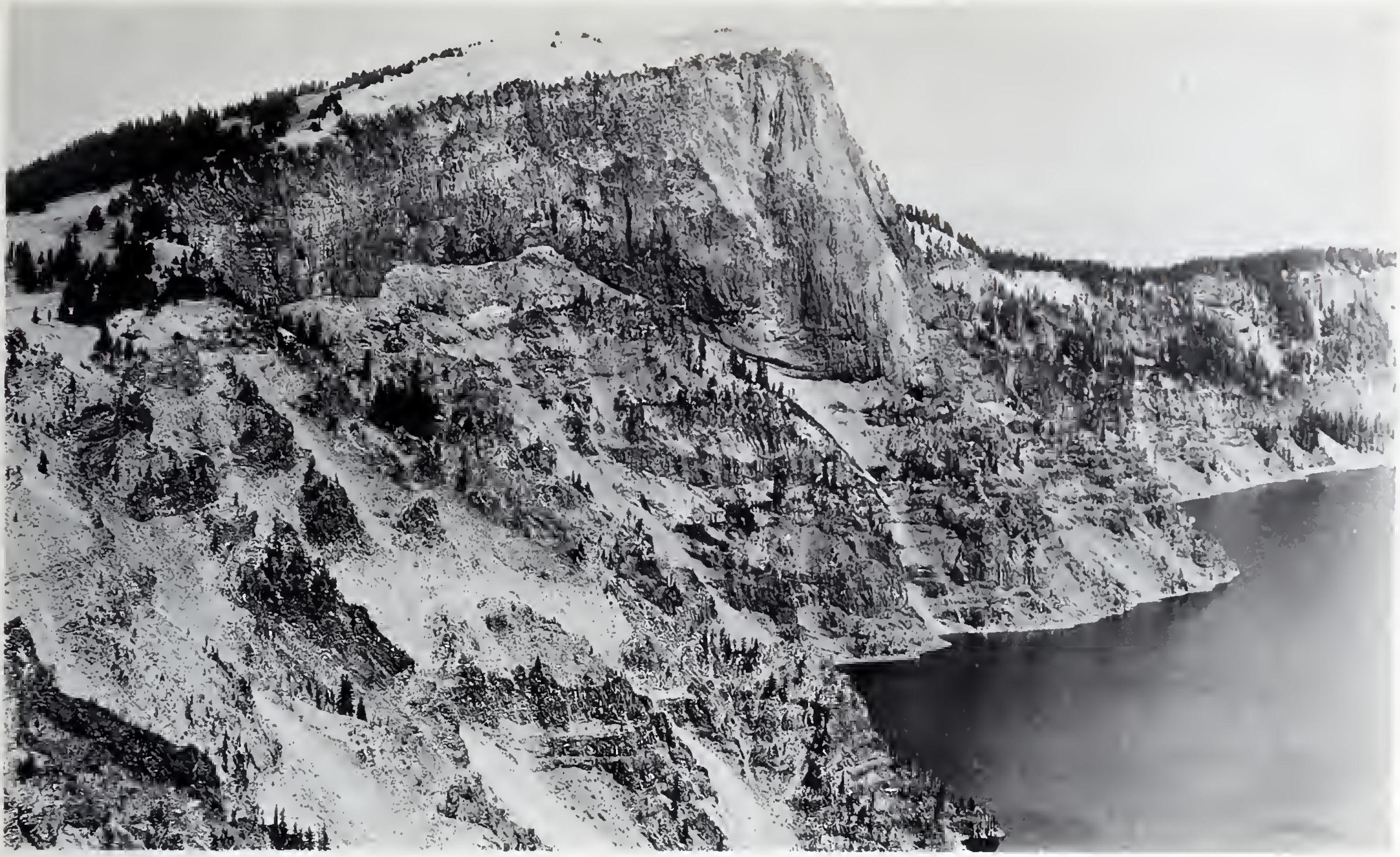


FIG. 1. The Llao Rock dacite flow. The feeder lies at the base of the main cliff. Above the flow lie bedded pumice deposits, products of the culminating eruptions of Mount Mazama. For explanation of pre-Llao deposits, see panoramas, plates 28 and 29. (Photograph by George Grant, National Park Service.)

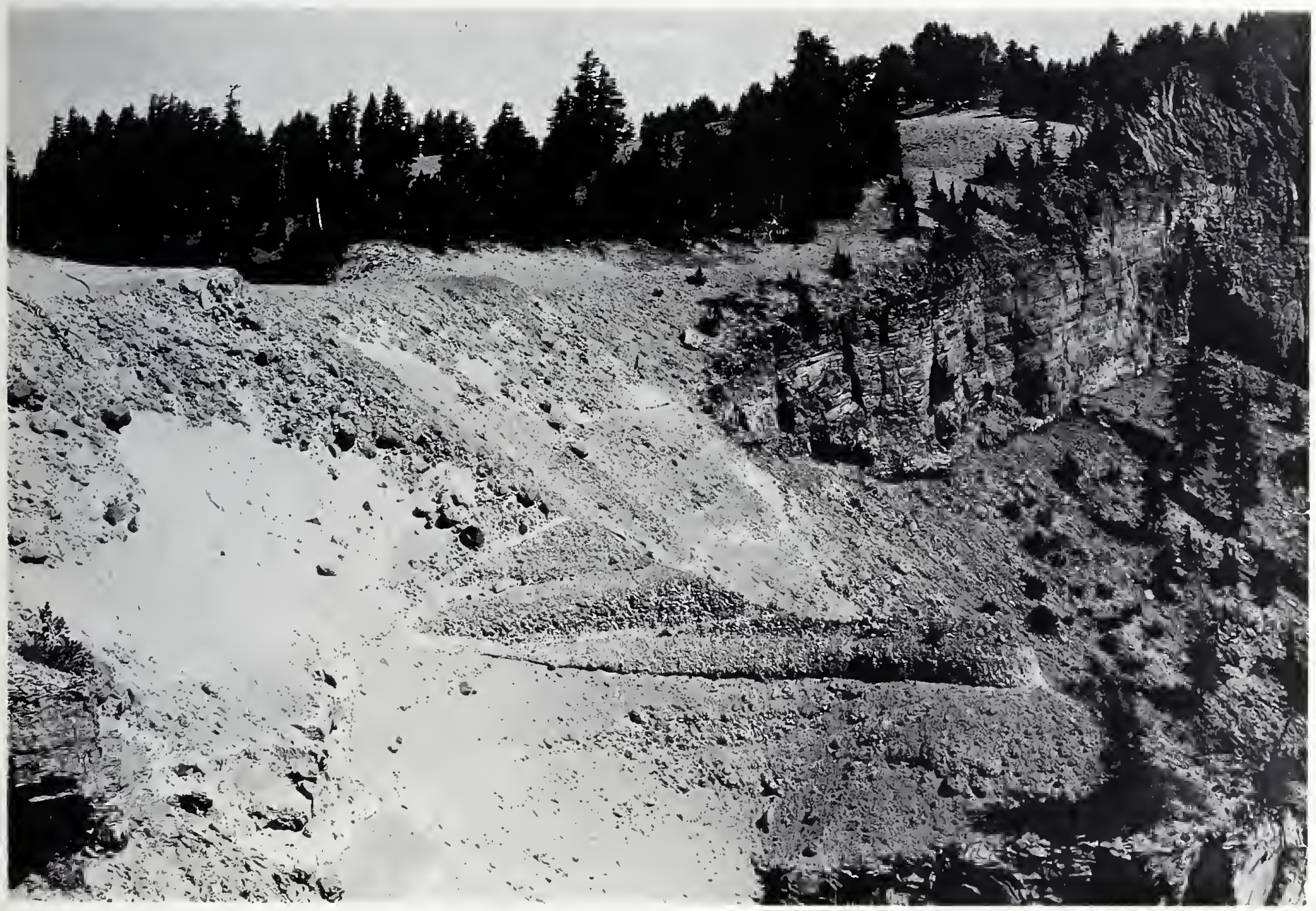


FIG. 2. West edge of the Llao Rock flow. Immediately under the flow, but almost entirely concealed by talus, is a layer of glacial debris. Coarse, bouldery glacial till also overlies the low margin of the flow and extends thence to the left, increasing in thickness. Near the center of the picture, this younger till is seen resting unconformably on dacitic lump pumice. This rests in turn on another layer of till, under which, at the bottom right corner, is a glaciated flow of andesite. (Photograph by George Grant, National Park Service.)

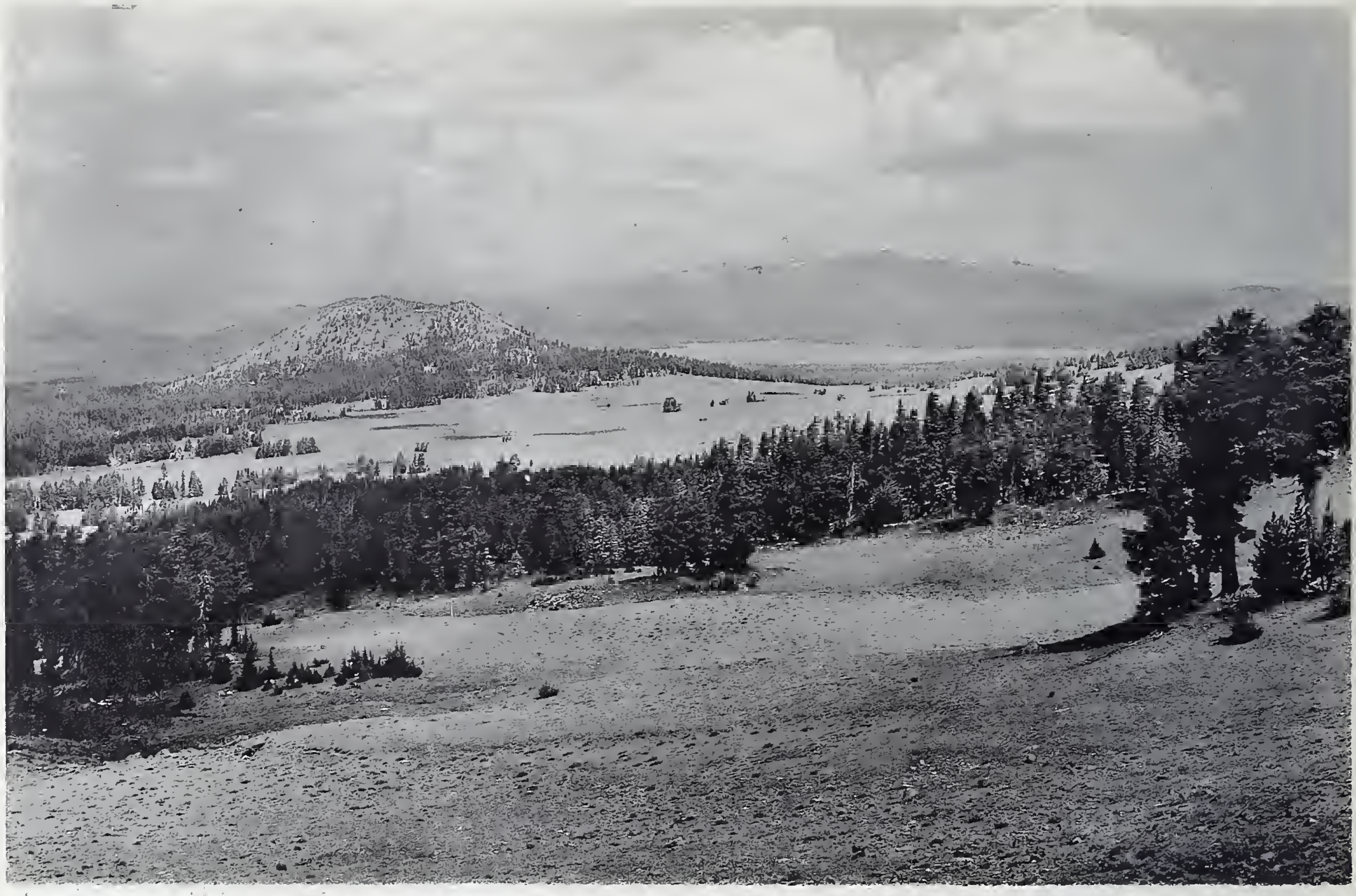


FIG. 1. Looking north across the Pumice Desert. Mount Thielsen in the distance. All the flat country is covered by deposits of pumice and scoria flows from Mount Mazama. The conspicuous hill in the middle distance is Red Cone, a scoria parasite of Mount Mazama. (Photograph by George Grant, National Park Service.)

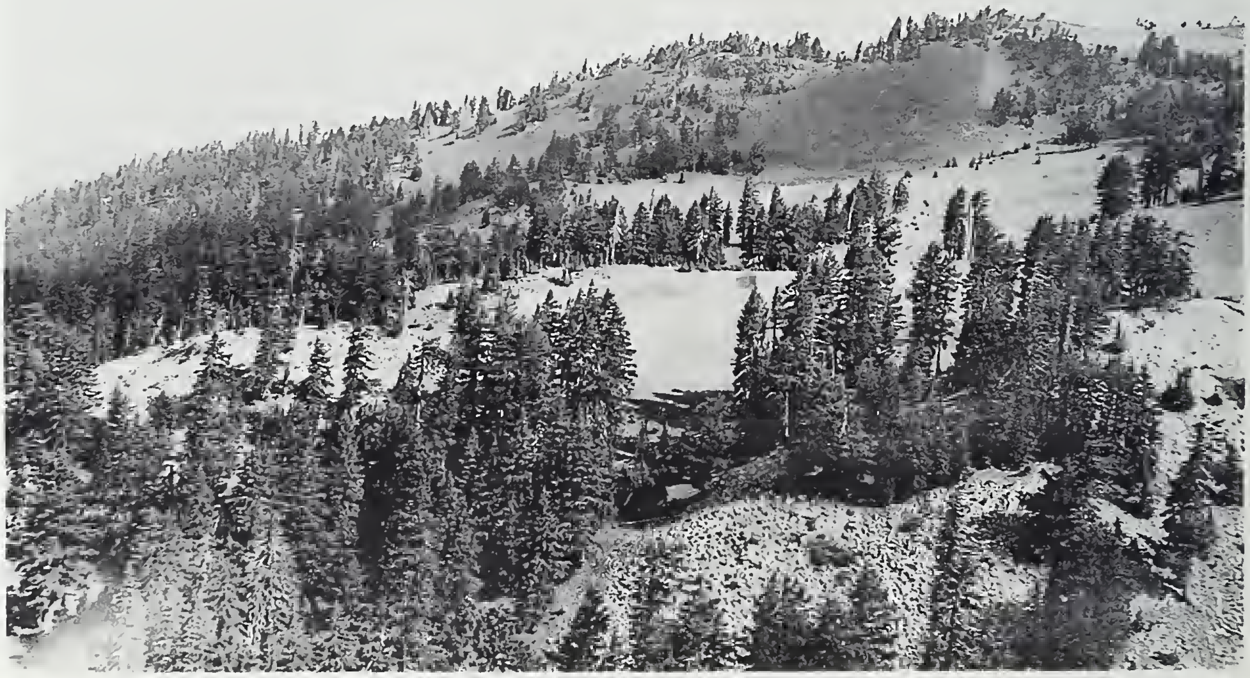


FIG. 2. Forgotten Crater, a denuded cinder cone west of Hillman Peak, looking north. A short lava flow can be seen just below and outside the crater rim. A much larger flow escaped from the west (left) base of the cone. Part of it forms the wooded ridge at the extreme edge of the picture.

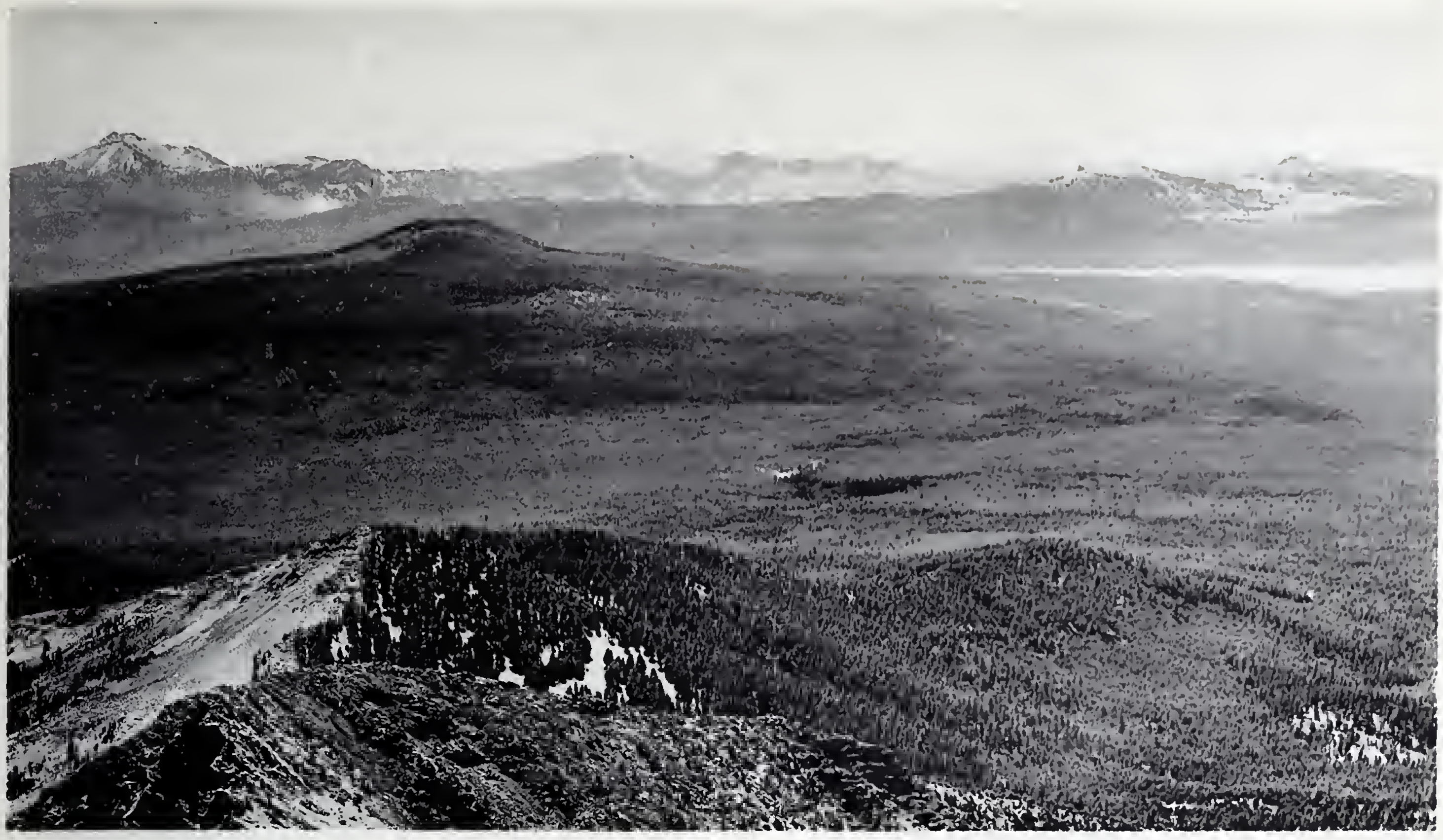


Fig. 1. Timber Crater and the rim of Crater Lake, from Mount Bailey. Mount Scott on the extreme left. The U-shaped valley beheaded by the far (south) wall of the caldera is Sun Notch. The bare patch on the extreme right is part of the Pumice Desert. In the middle distance is the symmetrical shield volcano of Timber Crater, with its summit cinder cone. (Photograph by Victor Duran.)

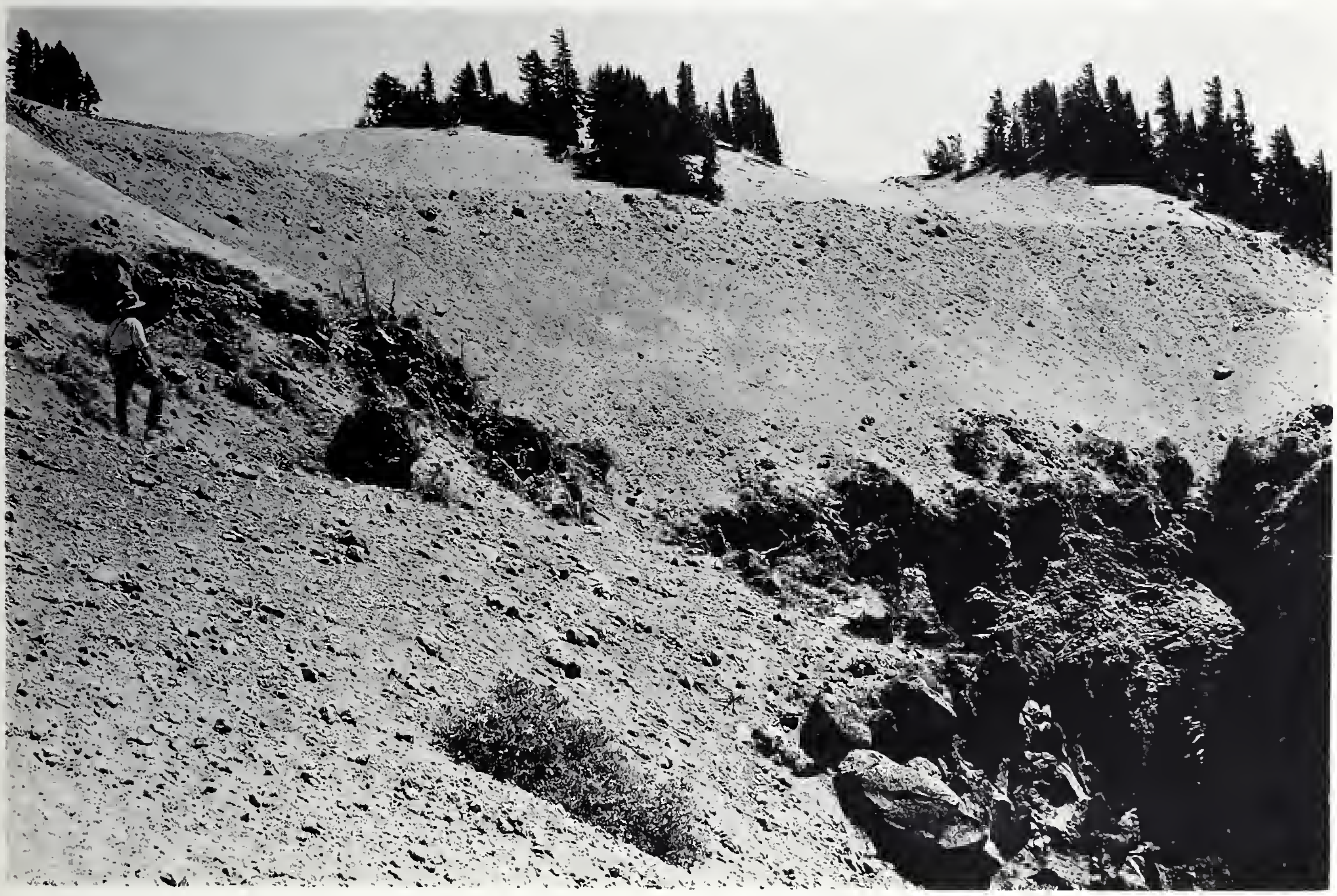


Fig. 2. Deposits on top of Sentinel Rock. Above the lava (lower right) lies glacial till, here concealed by talus. On this rest, first, lump pumice; then a coarse block layer, probably a moraine; and finally, on the rim, an upper layer of pumice, product of the culminating eruptions of Mount Mazama. See text, and figure 7*b*. (Photograph by George Grant, National Park Service.)

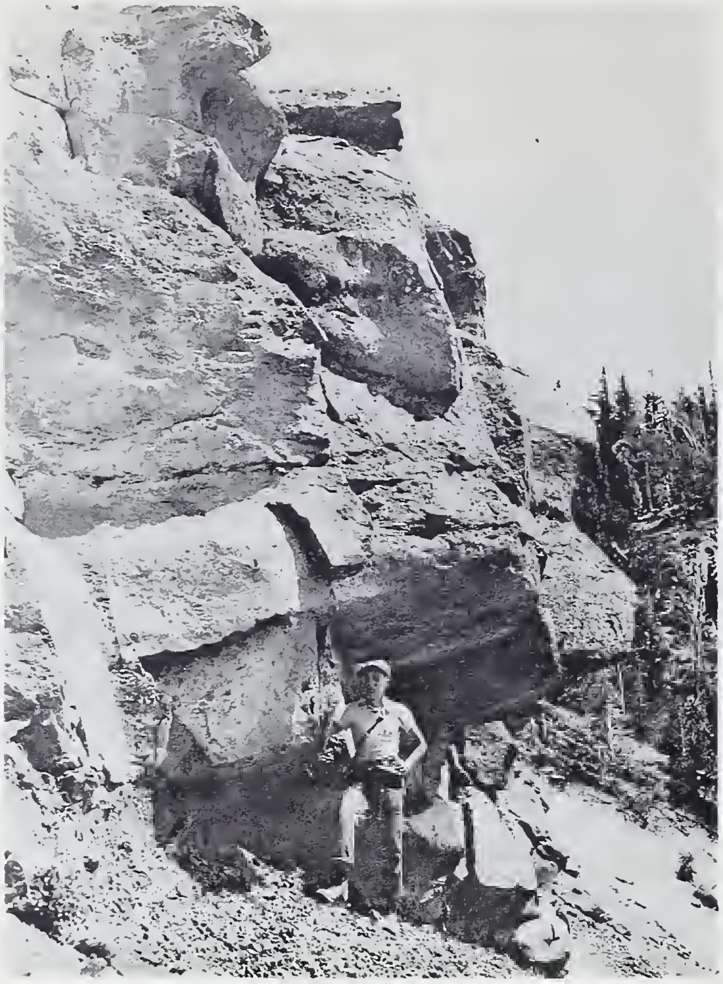


Fig. 1. Welded dacite tuff (ignimbrite) forming the brim of the Wineglass. The figure stands on coarse, incoherent lump pumice. Upward this grades rapidly into the cliff-forming welded tuff, the pronounced streaky banding of which simulates the flow banding of lava.

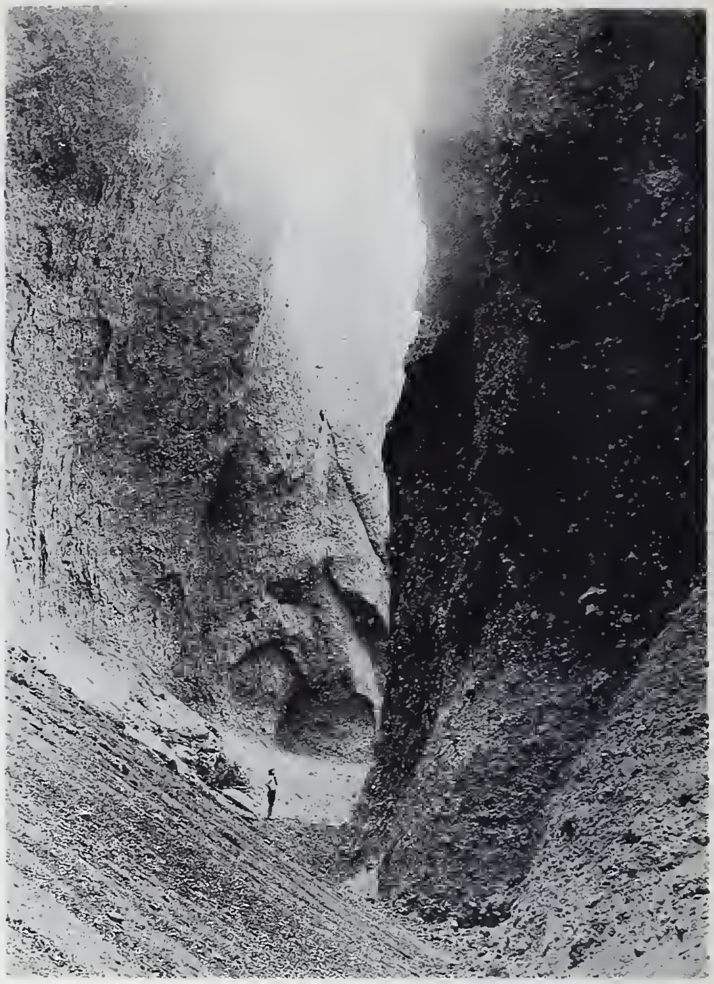


Fig. 2. Llao's Hallway, a tributary canyon on the south side of Castle Creek, cut in massive, unbedded, chaotic deposits of a scoria flow (*nuée ardente*). (Photograph by National Park Service.)

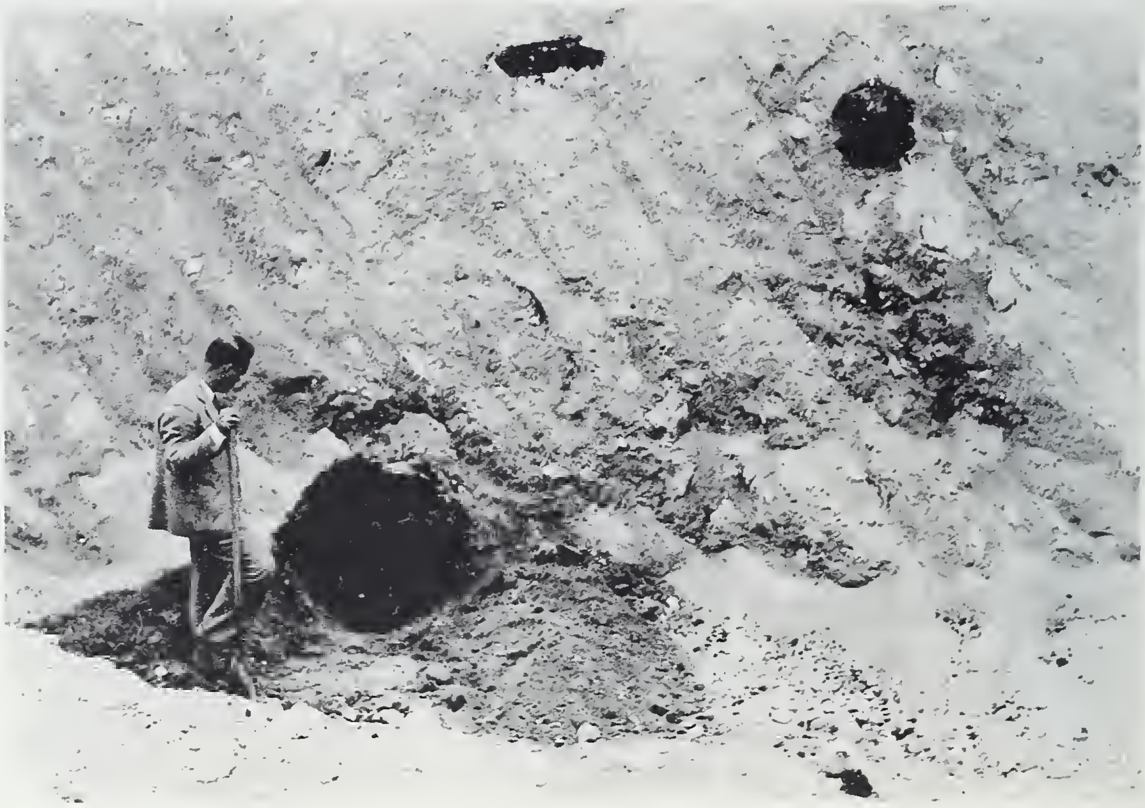
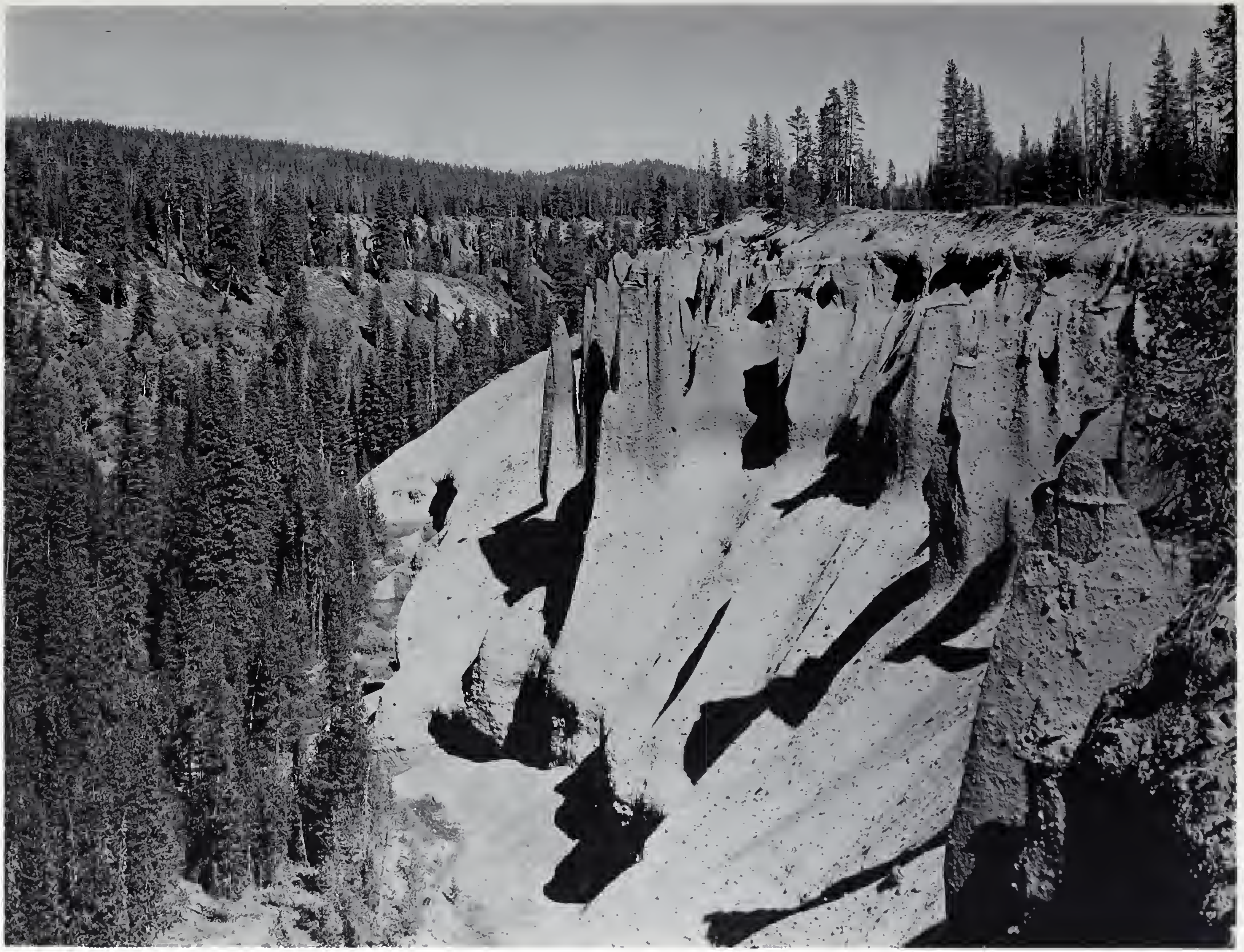


Fig. 3. Charcoal logs in deposits of a pumice flow, on Diamond Lake highway, a mile above the Union Creek junction. (Photograph by National Park Service.)



The Pinnacles, Sand Creek canyon, showing pale pumice flow beneath smoke-gray scoria flow, above which lie 10 feet of fine ash. Near the contact of the ash and scoria layers is the red zone caused by oxidation of iron-bearing fumarole gases. The pinnacles result from erosion controlled partly by vertical joints and partly by local compaction of scoria by hot gases. (Photograph by George Grant, National Park Service.)

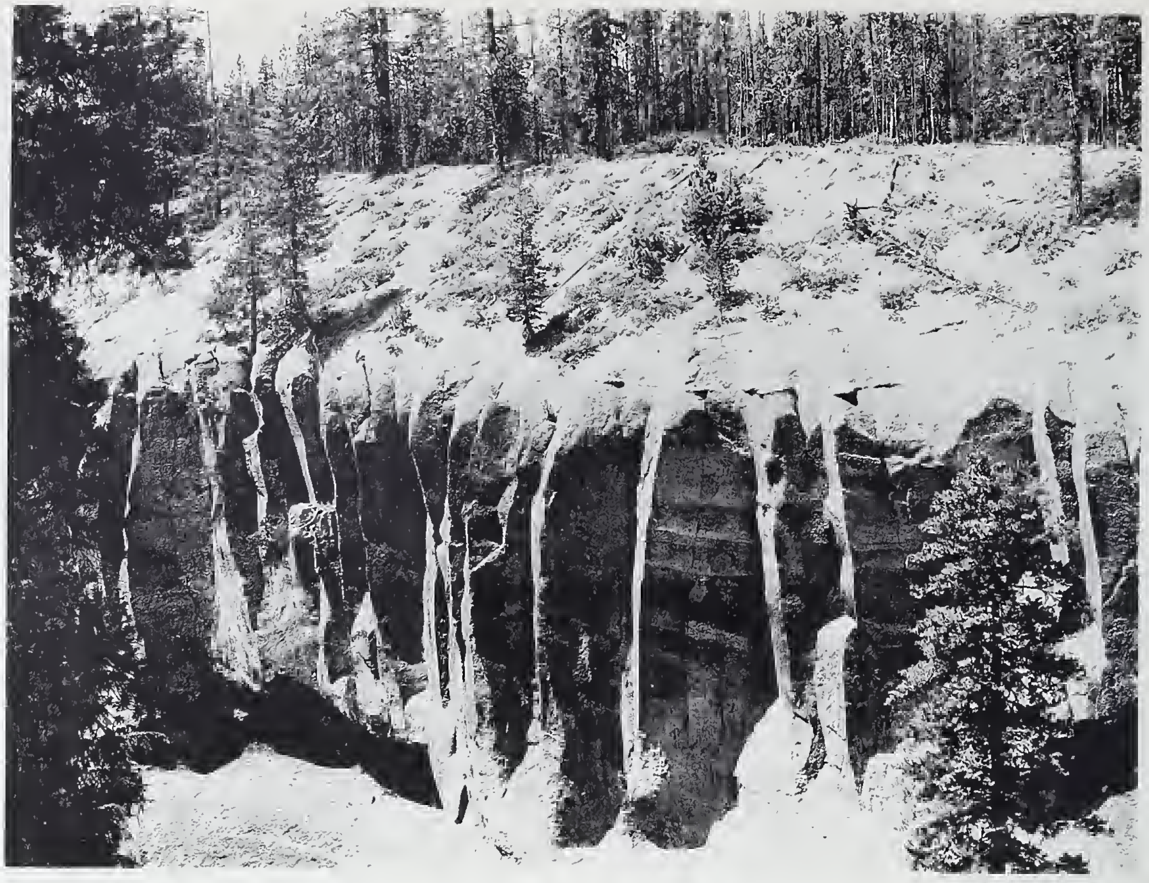


FIG. 1. Columnar scoria flow overlain by crystal- and lithic-rich ash, Annie Creek canyon. (Photograph by William Schoeb.)

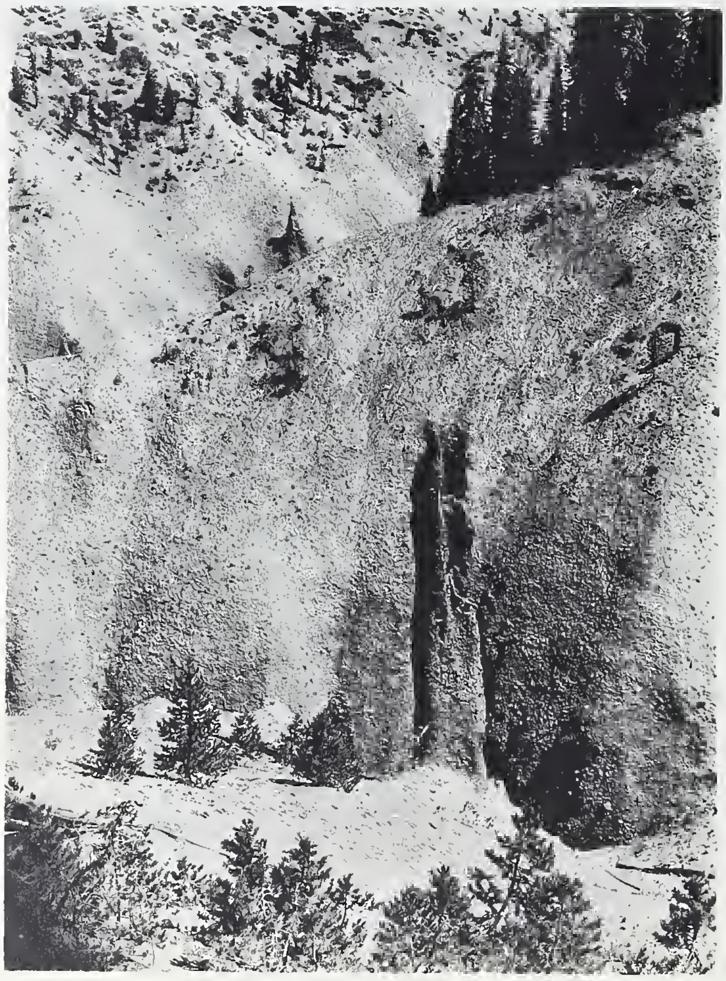


FIG. 2. "Fossil fumarole" in Castle Creek canyon. Note figure at the base for scale; note also the massive, unbedded, coarse nature of the deposits on the far wall of the canyon. (Photograph by National Park Service.)

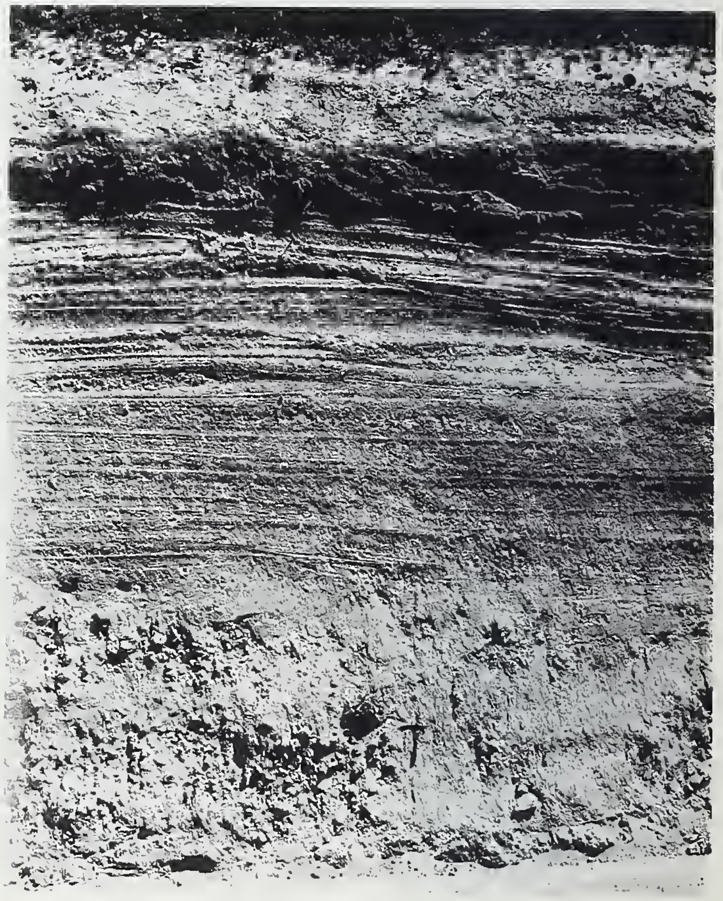


FIG. 3. Pumice deposits on Diamond Lake highway. At the base, 4 feet of coarse, unbedded pumice-flow deposits containing a charcoal log (near hammer). Above, bedded, fine pumice fall. The dark band near the top is the pink zone caused by oxidation of fumarolic gases rising from the pumice flow at the base. This indicates that the fine pumice fell on the flow while it was still hot.

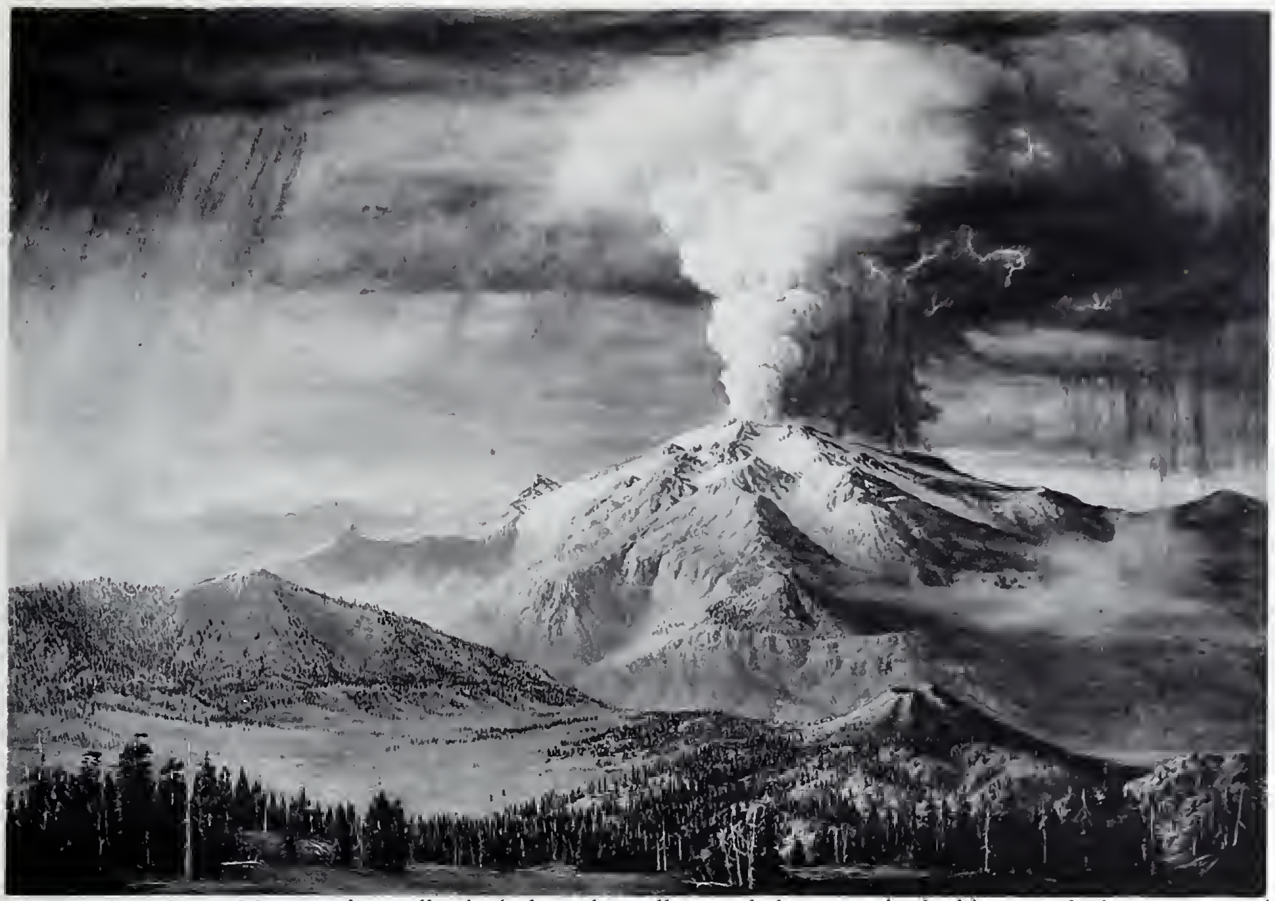


FIG. 1. Mount Mazama immediately before the collapse of the summit, looking north from near Union Peak. From a painting by Paul Rockwood. Shows the general configuration of the volcano when the culminating eruptions began. Wind blowing to the northeast, carrying granular pumice. Typical cauliflower eruption clouds such as must have formed during the opening activity. The three glaciers on the south slope of the volcano are, from left to right, the Munson, Sun, and Kerr Valley glaciers. Below them stretch bare, U-shaped glacial canyons. The small cone near the center of the picture is the parasitic Crater Peak. Pumice Flat in left foreground.

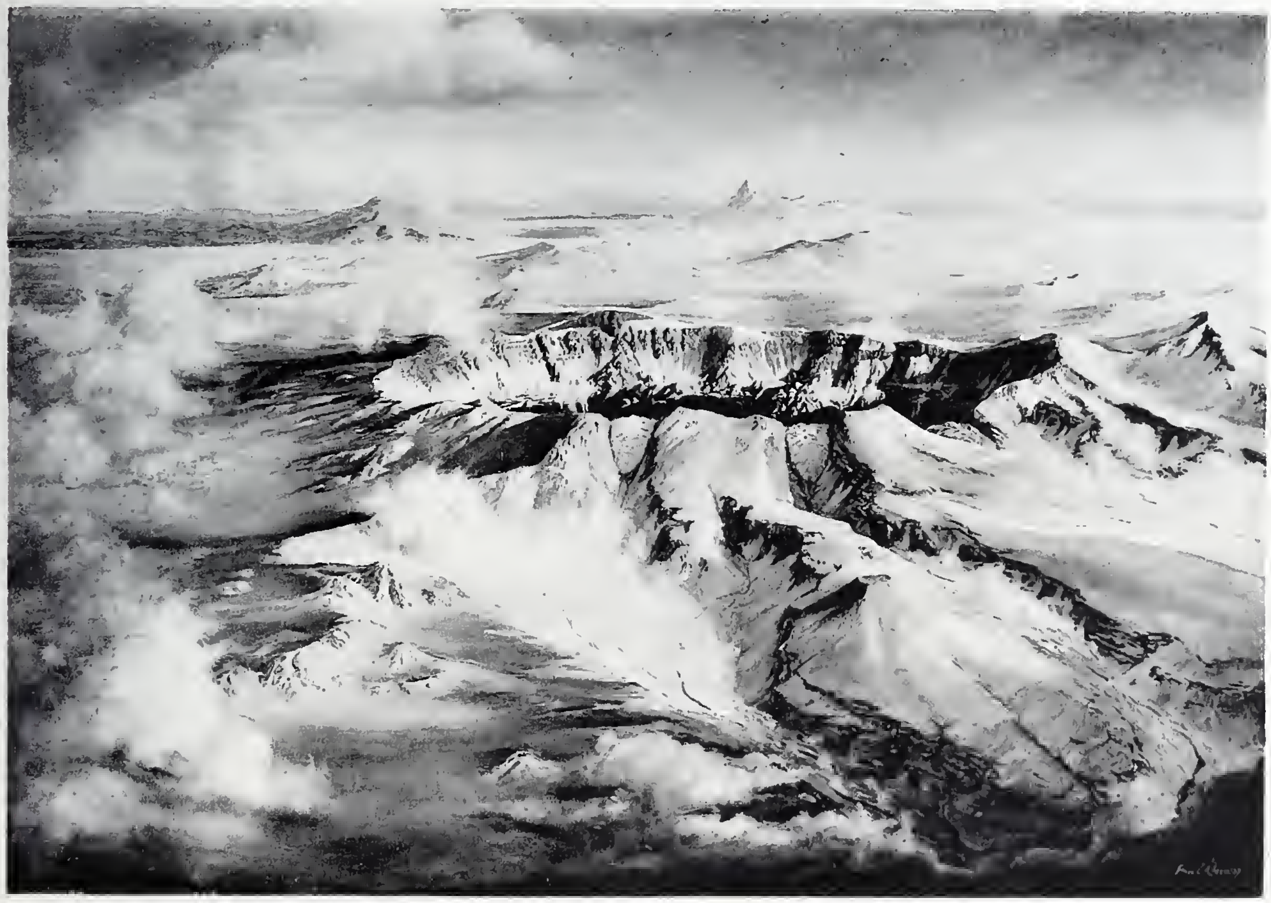


FIG. 2. Mount Mazama immediately after the collapse of the summit. From a painting by Paul Rockwood. Compare figure 1, above. Note that the U-shaped glacial canyons have been filled with the deposits of glowing avalanches (*nuées ardentes*), from which countless fumaroles give off gas. The plains beyond the caldera are also covered with pumice-scoria flows which discharge fumaroles. Note that pumice is almost absent on the west (left) slope of the volcano and thickens toward the east. The beheaded glaciers of Munson, Sun, and Kerr valleys are shown. The caldera floor lies approximately 2000 to 4000 feet below the rim.

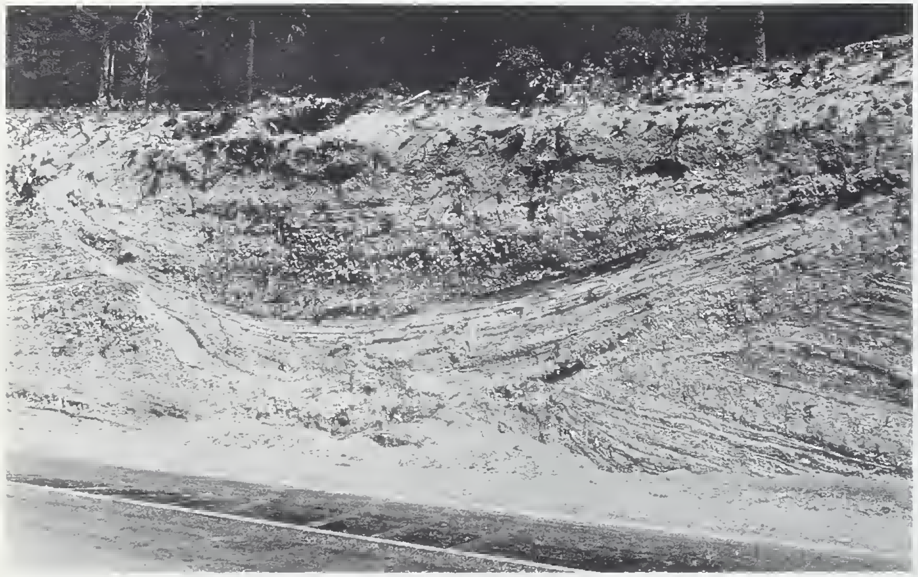


Fig. 1. A channel among the bedded pumice deposits, on Diamond Lake highway, below the Rogue River bridge.

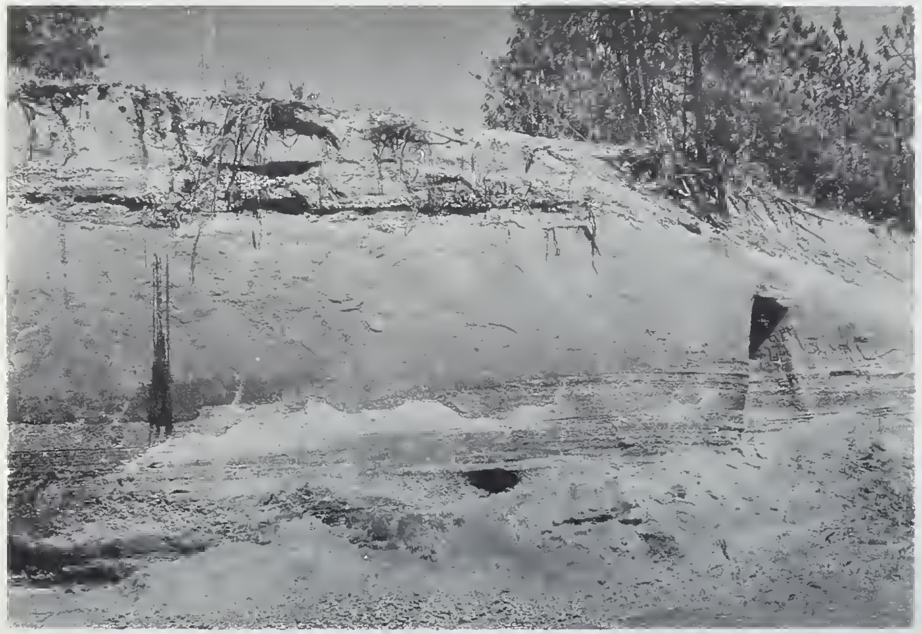


Fig. 2. Washed and bedded pumice deposits, in a roadside quarry near Rogue-Elk junction, Medford highway, a few miles below the snout of the Rogue River pumice flow. Essentially a mass of rolled pumice fragments, mixed with andesitic gravel and containing many chips of charcoal washed from the pumice flows upstream.

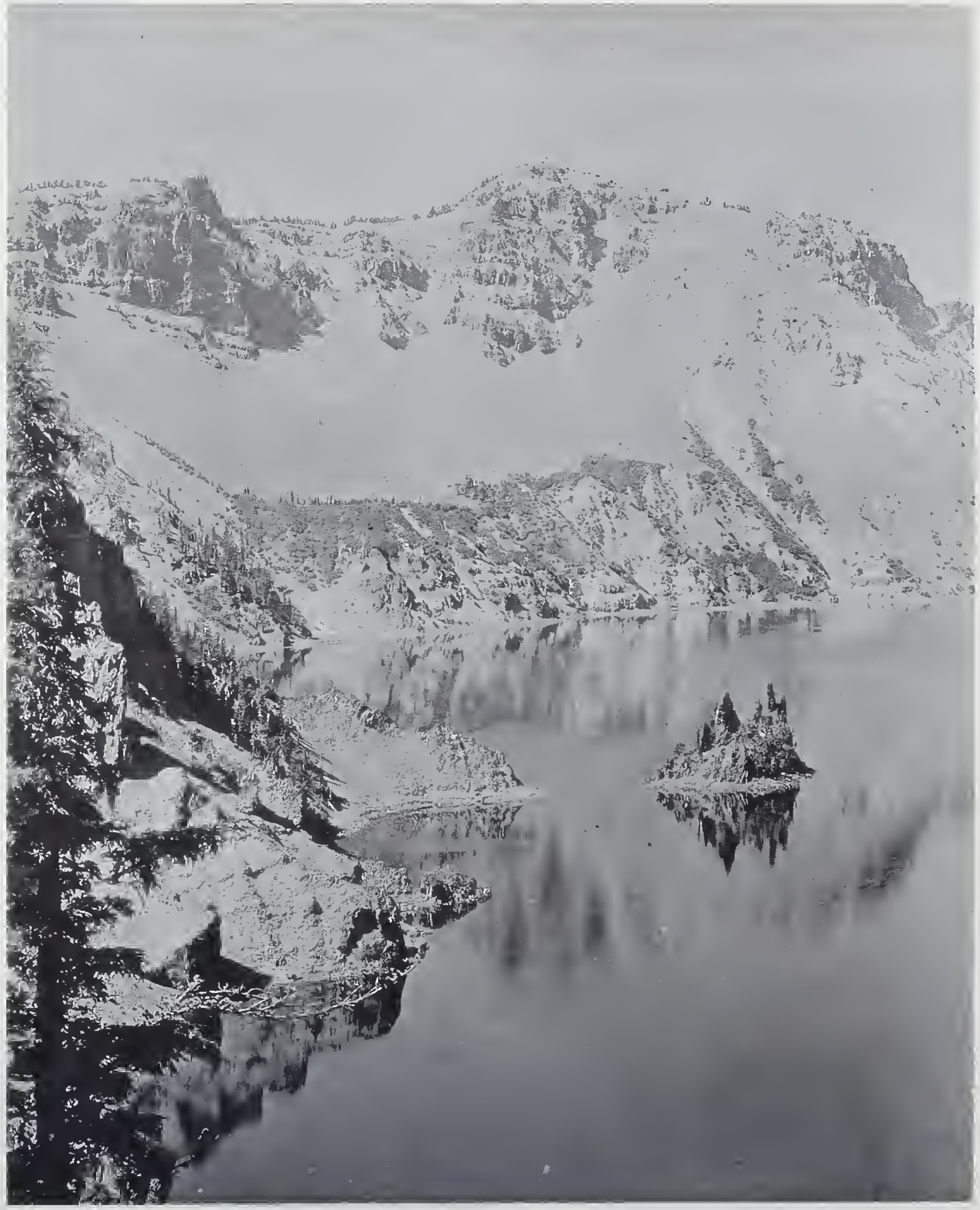
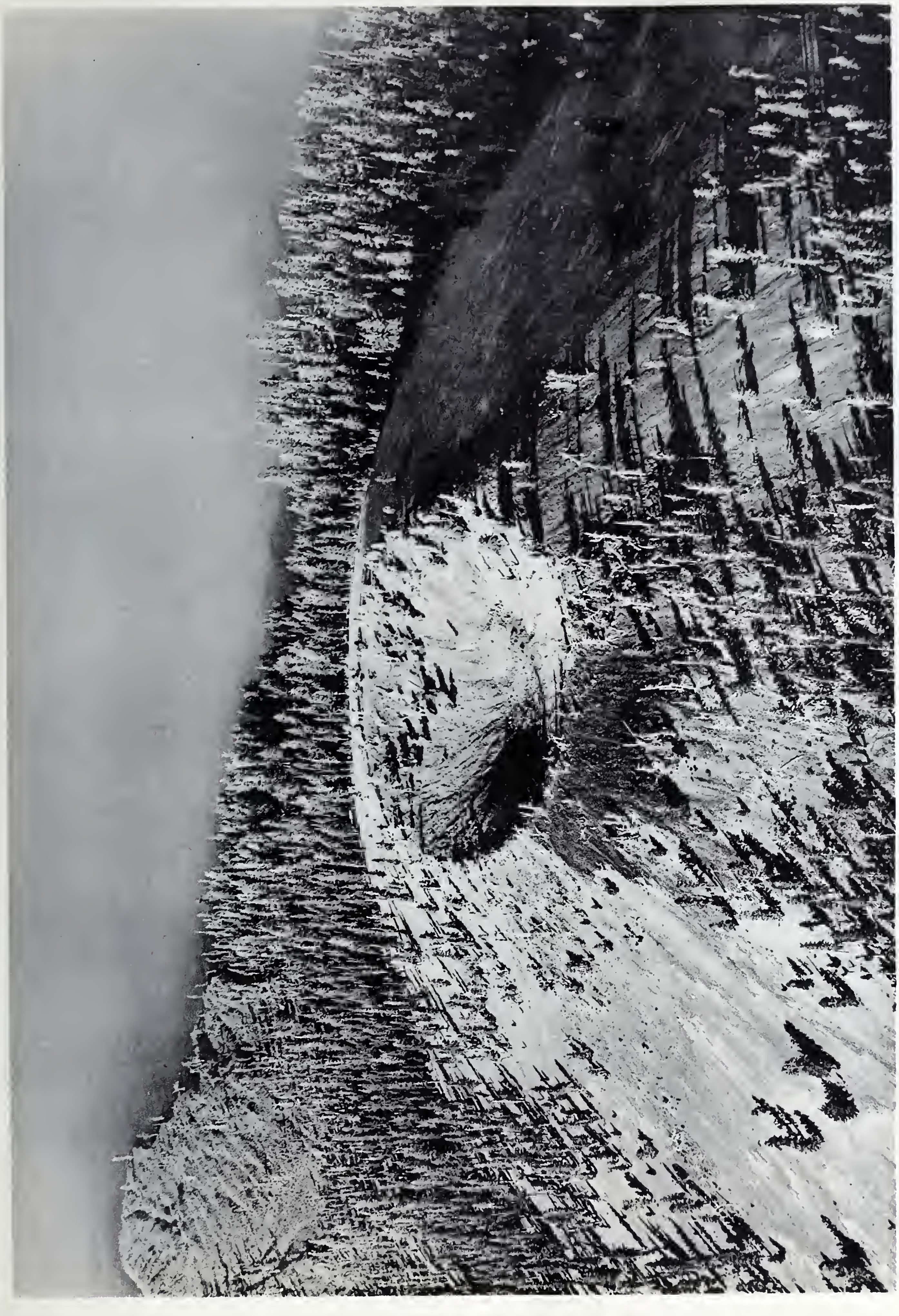


Fig. 3. View from Kerr Notch. Beyond Phantom Ship, at the foot of the caldera wall, is the Chaski landslide block, above which tower Applegate and Garfield peaks. (Photograph by George Grant, National Park Service.)



Aerial view of the cone of Wizard Island. (Photograph by U. S. Army Air Corps.)

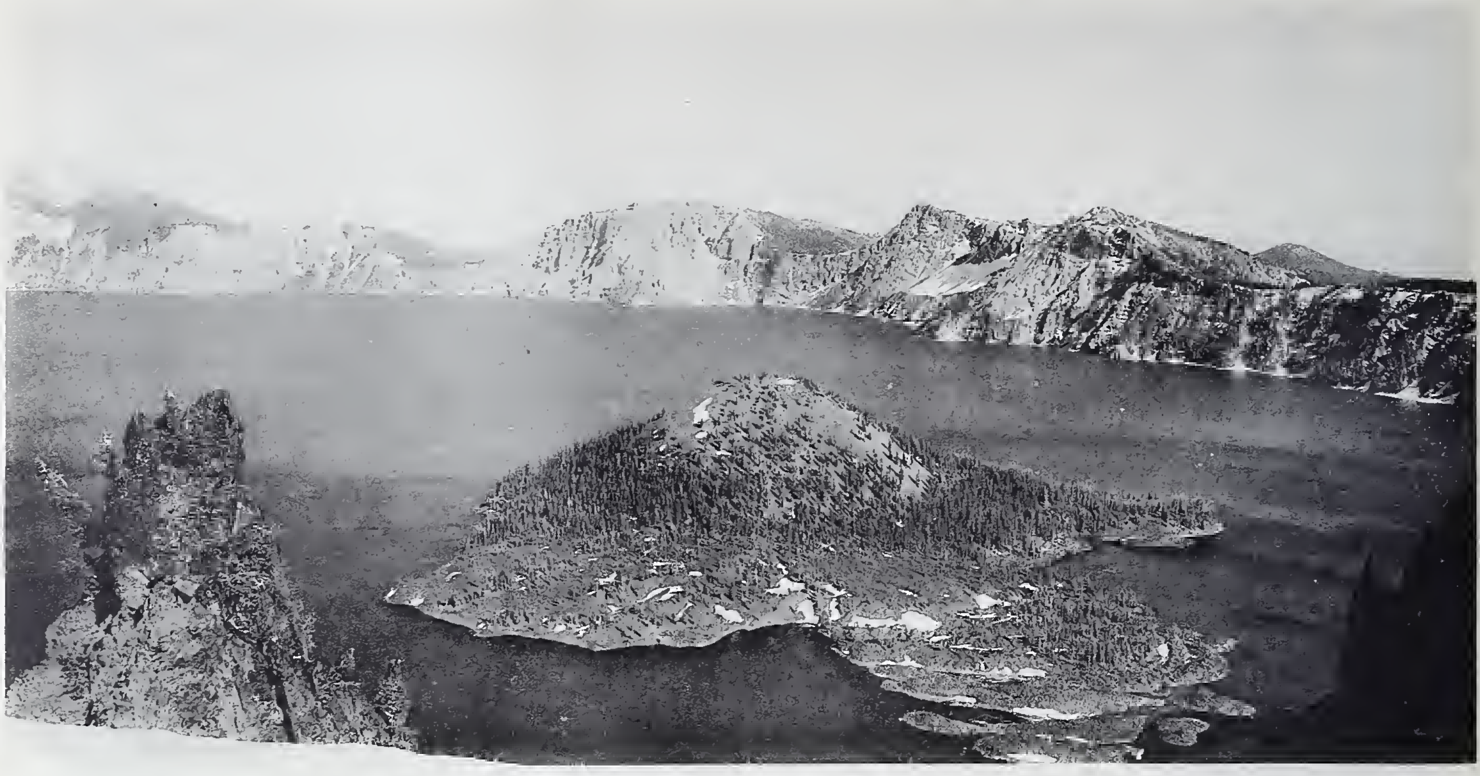


Fig. 1. The southeast wall of the caldera, and Wizard Island. From left to right: Mount Scott; Kerr and Sun notches with Dutton Cliff between; Applegate and Garfield peaks, with the Chaski slide between. Farther to the right, in the background, rises Crater Peak, a parasitic cinder cone. The arcuate block ridges on the flow from the Wizard Island cone are emphasized by snow banks in the intervening hollows. (Photograph by H. B. Taylor.)

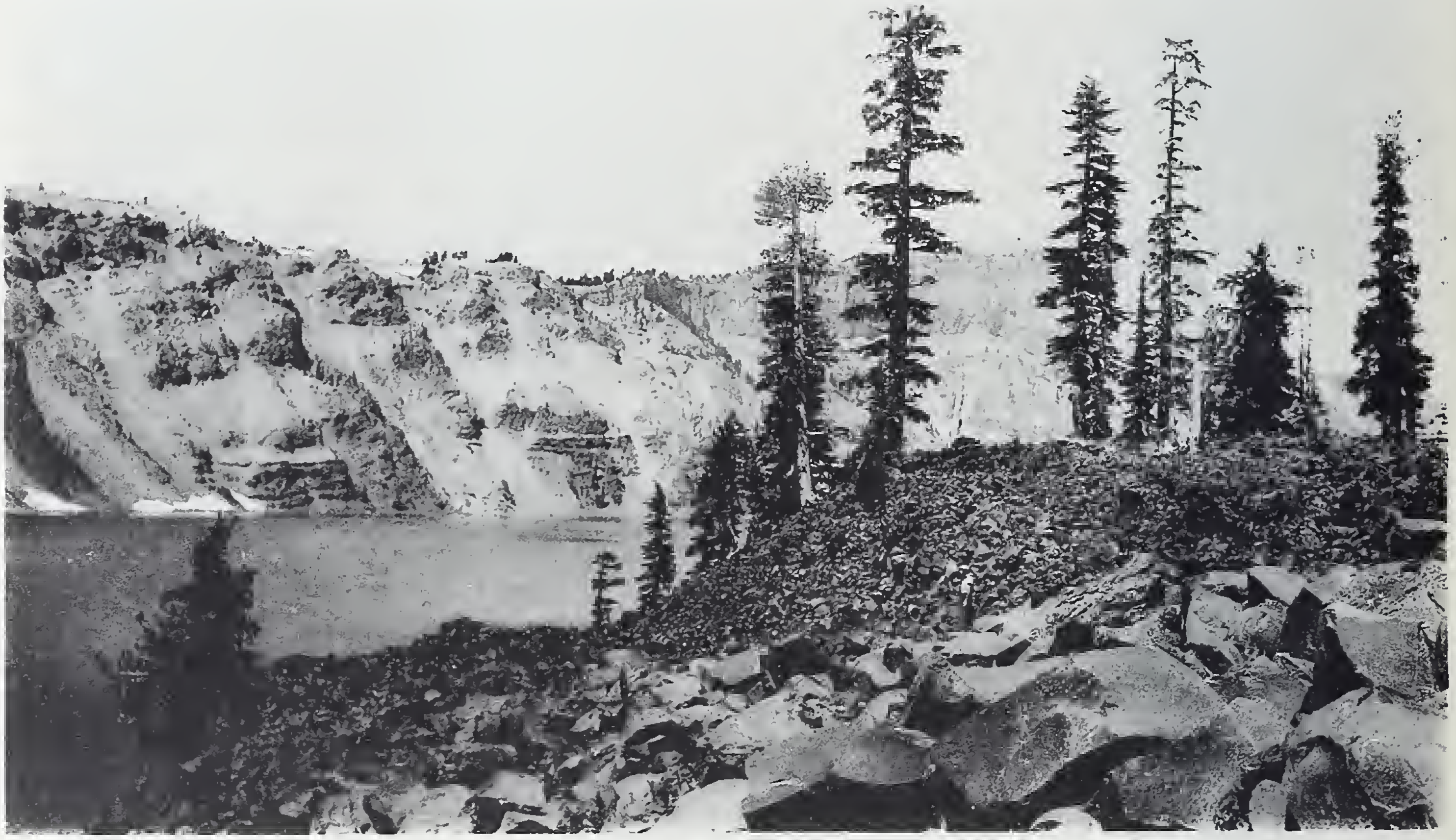


Fig. 2. Lava flows on Wizard Island. The figure stands at the junction between the coarse block lava and the finer, scoriaceous lava.

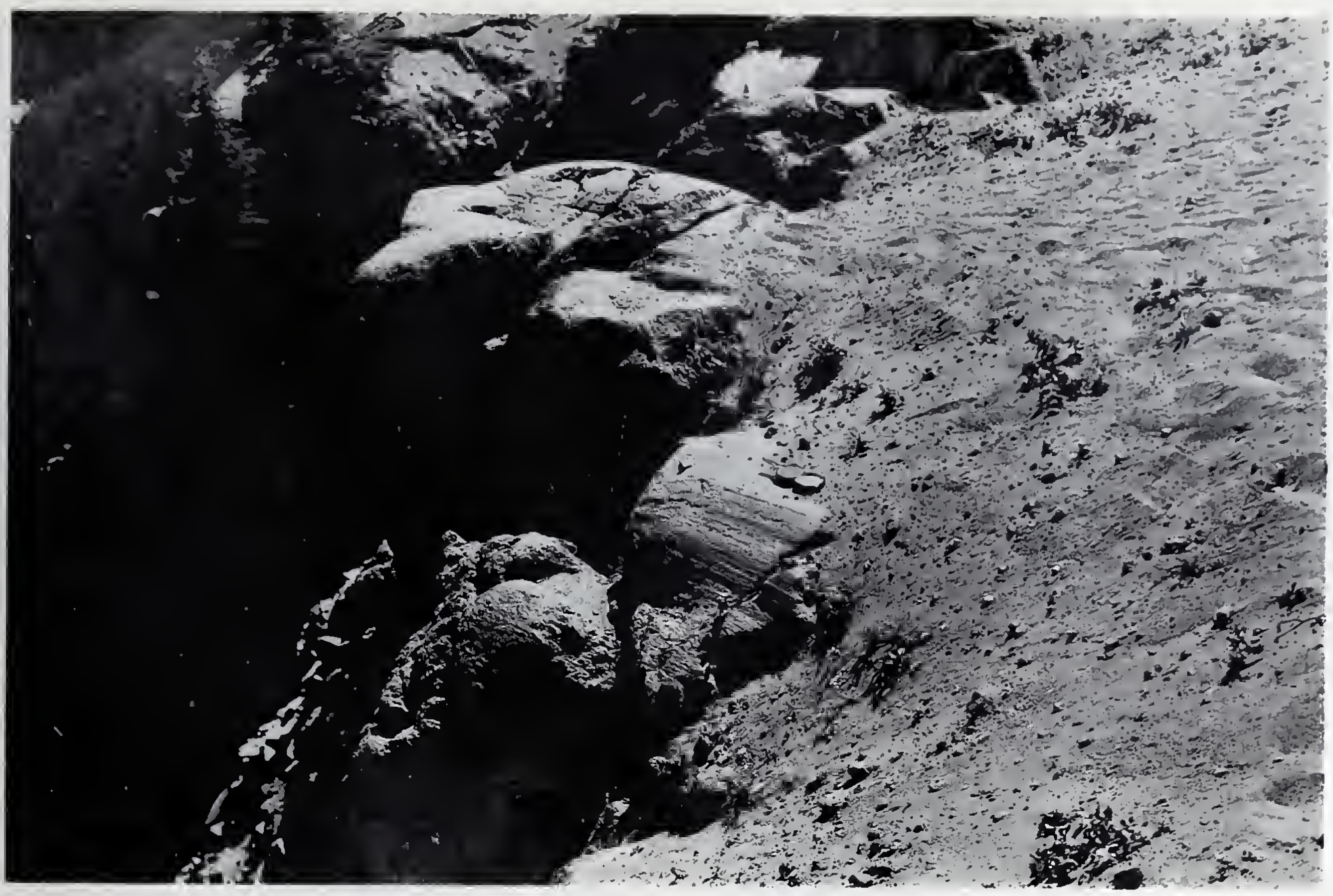


FIG. 1. Typical glacial striae on the caldera rim near Discovery Point. The overlying deposits are of pumice charged with lithic fragments. (Photograph by George Grant, National Park Service.)

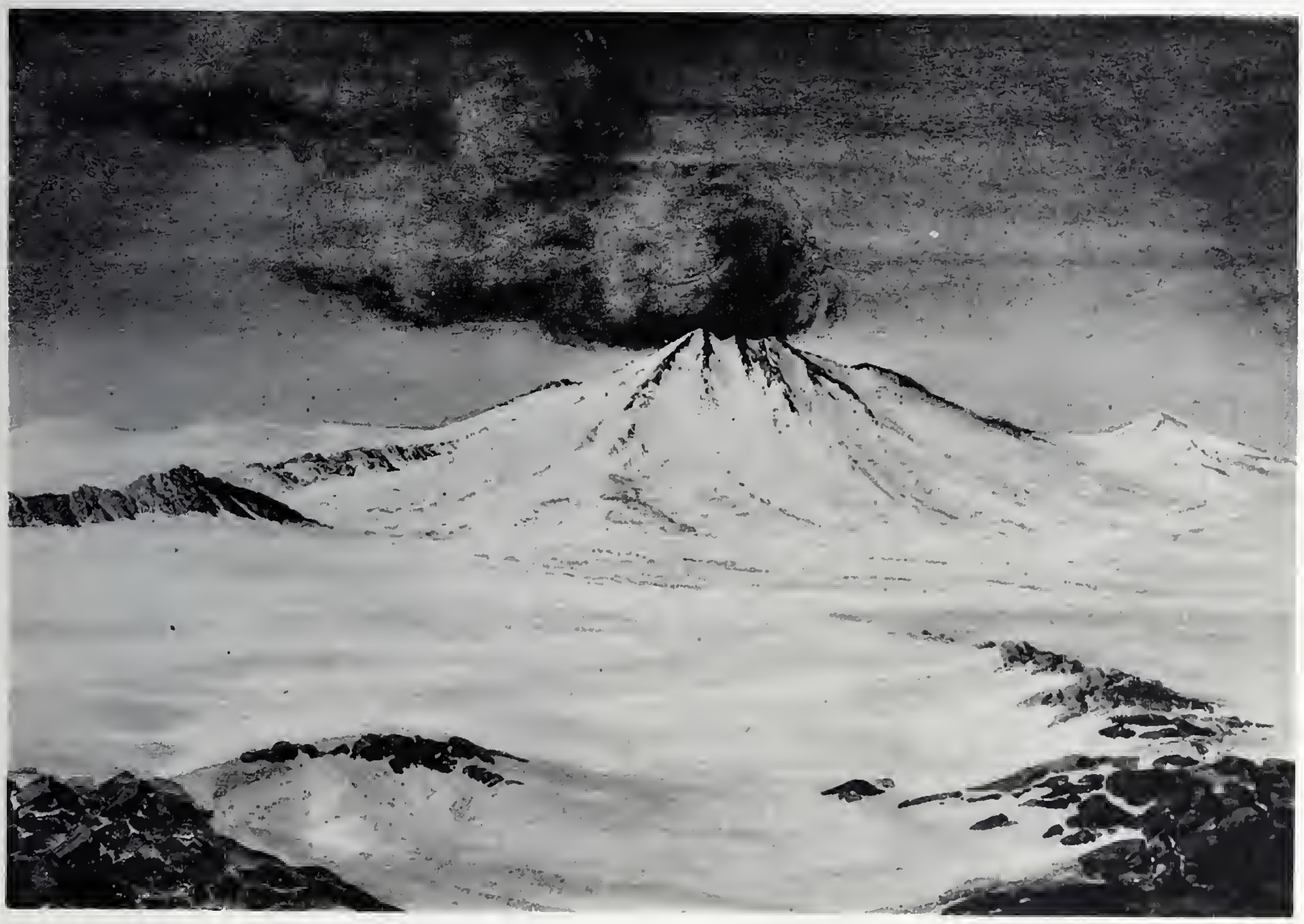
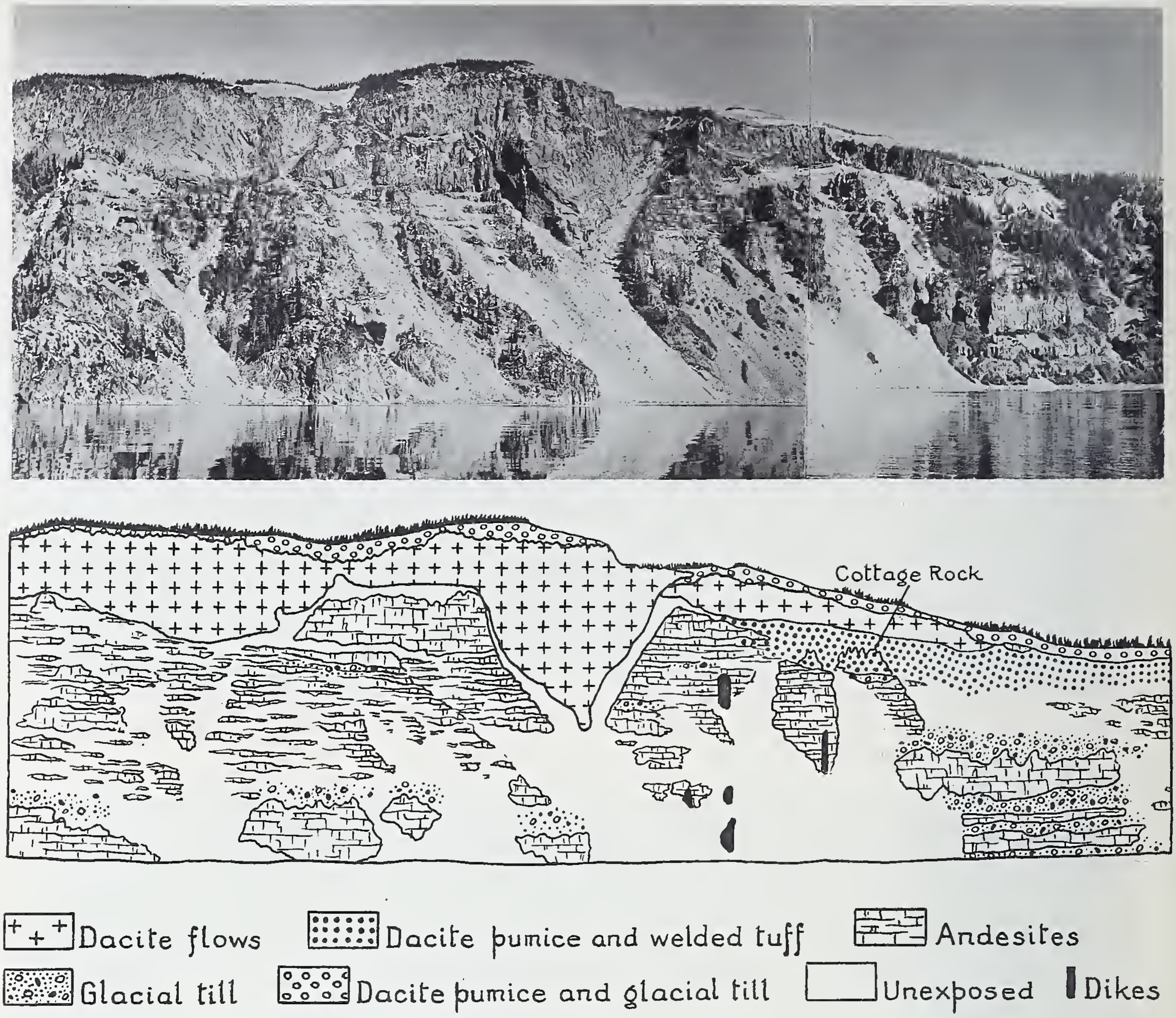
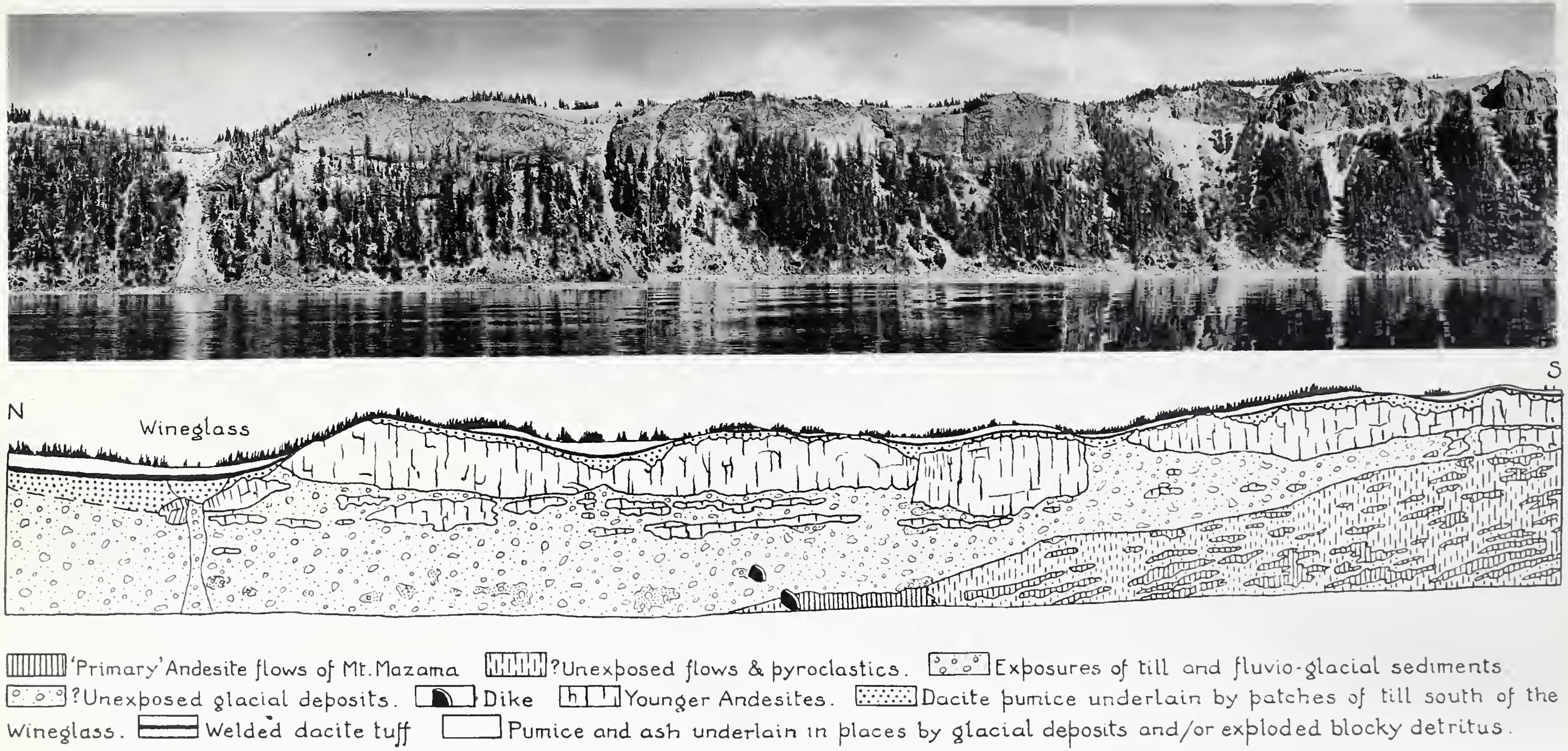


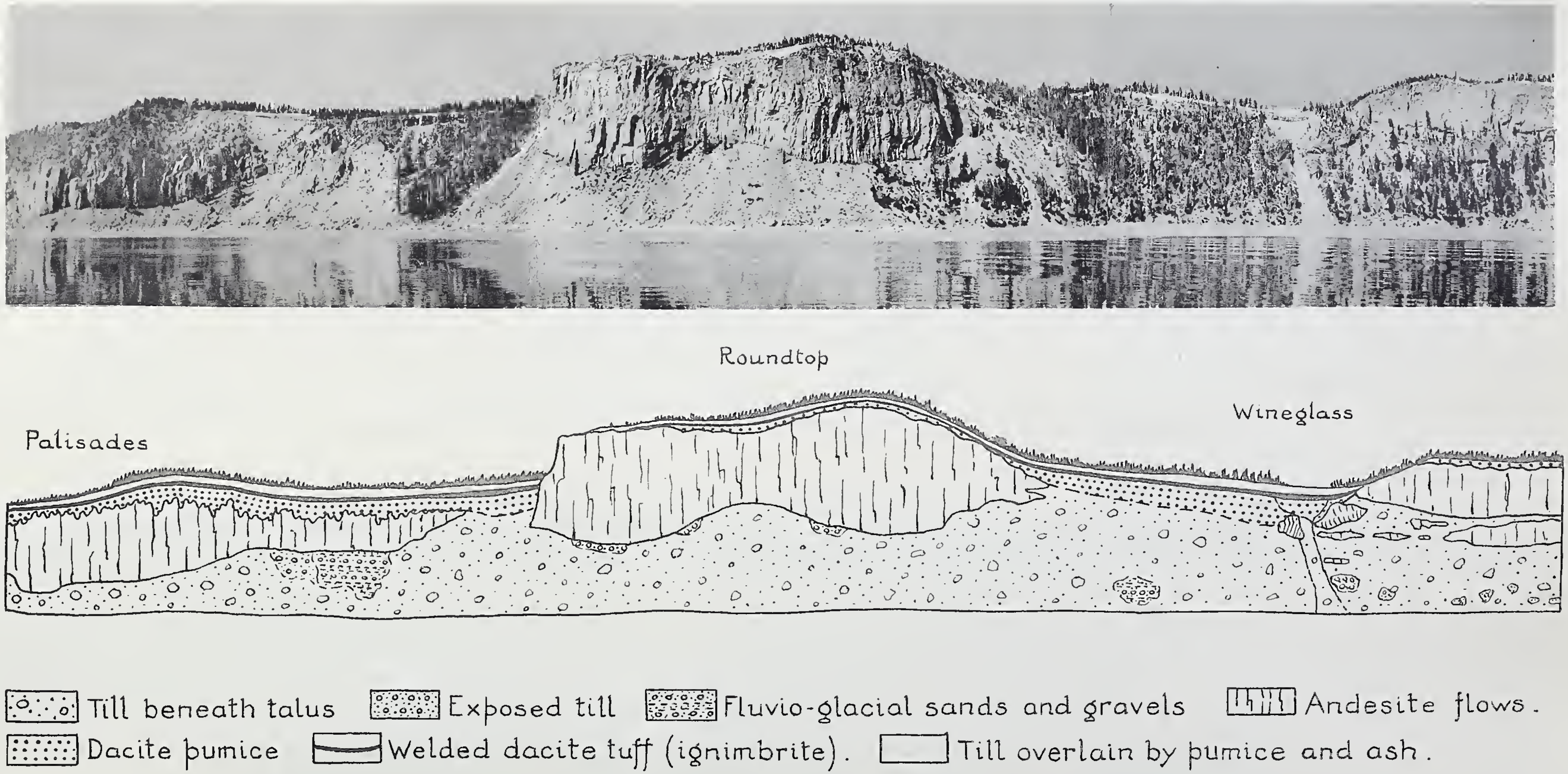
FIG. 2. Mount Mazama at the time of maximum glaciation, looking north. From a painting by Paul Rockwood.



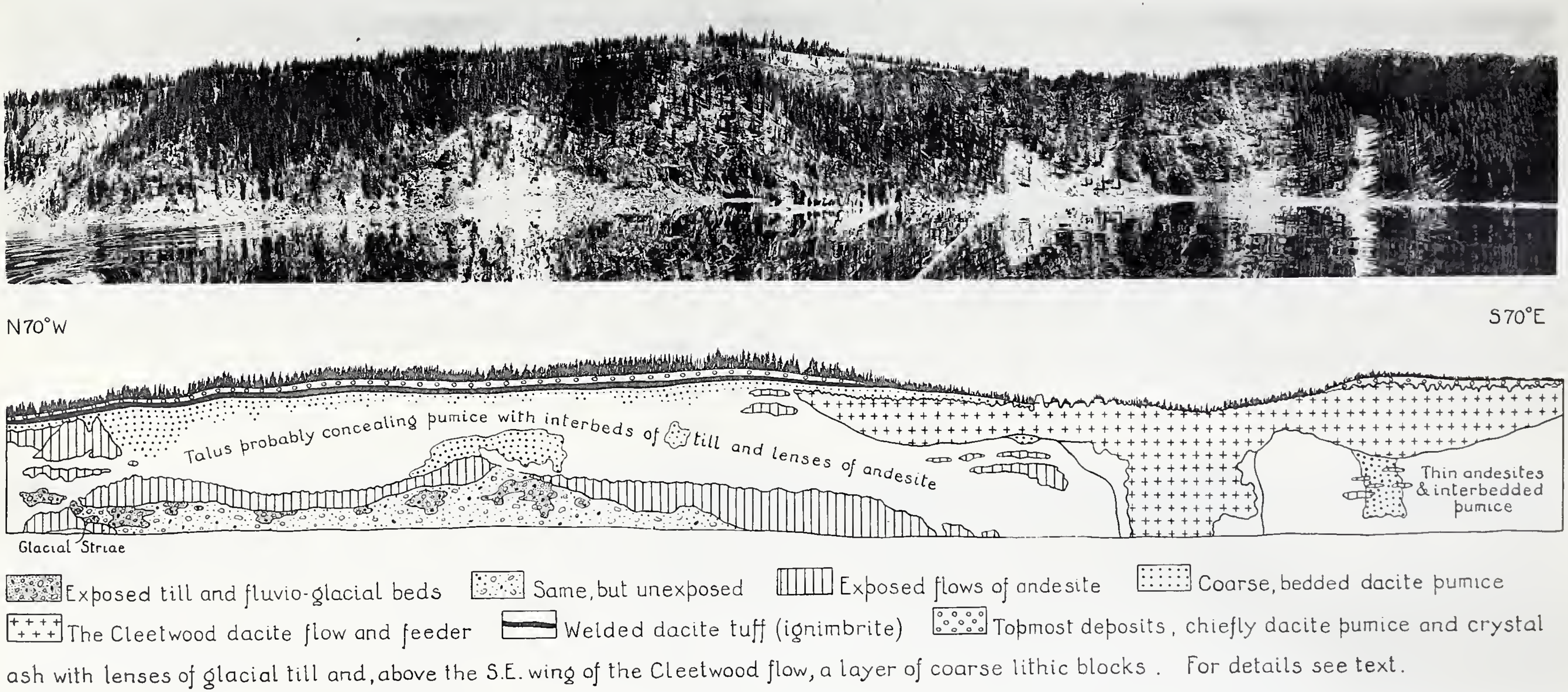
Panorama of the caldera wall: Cloudcap Bay


N
Wineglass
S
'Primary' Andesite flows of Mt. Mazama
?Unexposed flows & pyroclastics.
Exposures of till and fluvio-glacial sediments
?Unexposed glacial deposits.
Dike
Younger Andesites.
Dacite pumice underlain by patches of till south of the Wineglass.
Welded dacite tuff
Pumice and ash underlain in places by glacial deposits and/or exploded blocky detritus.

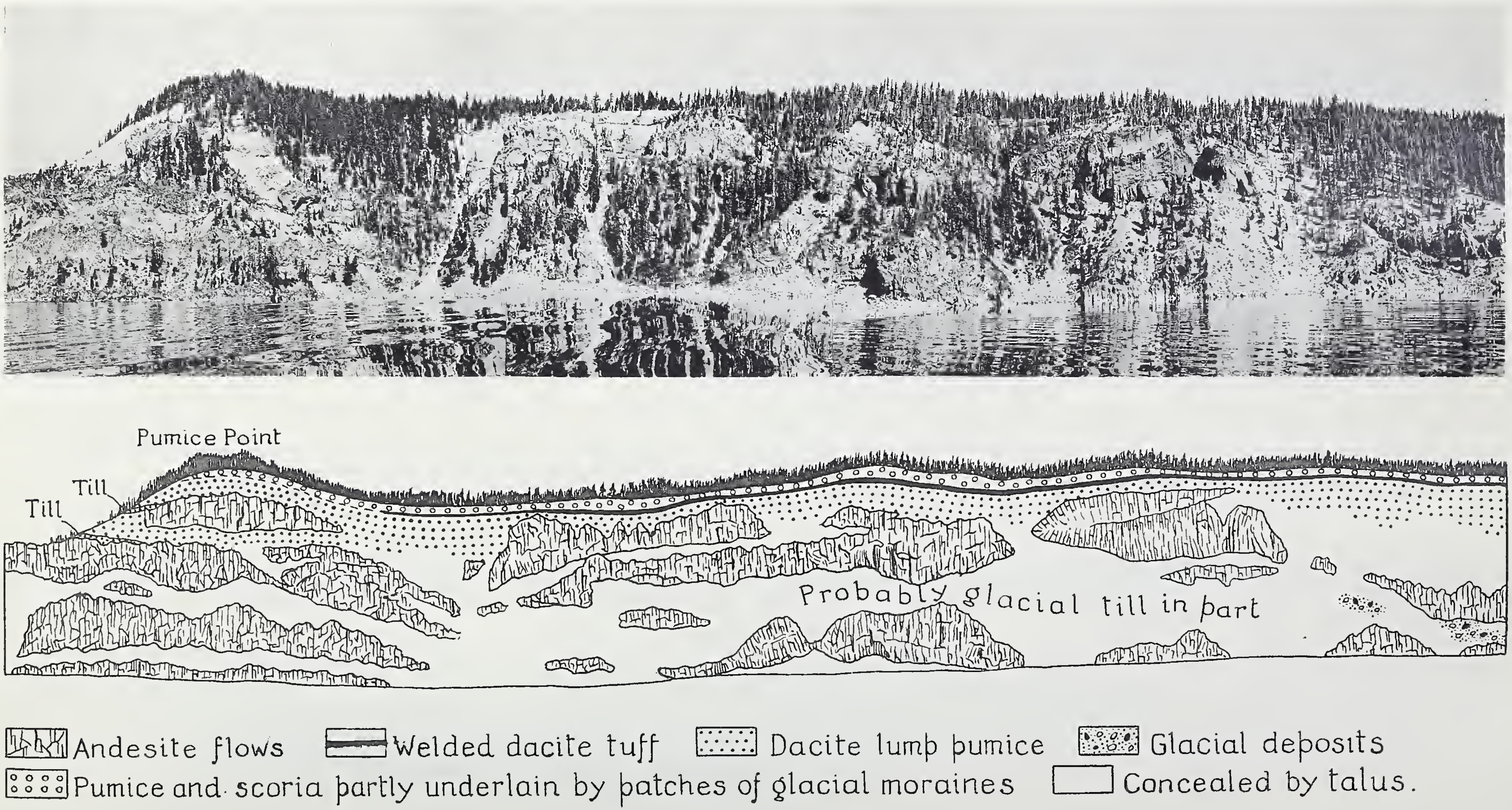
Panorama of the caldera wall: Grotto Cove


Roundtop
Palisades
Wineglass
Till beneath talus
Exposed till
Fluvio-glacial sands and gravels
Andesite flows.
Dacite pumice
Welded dacite tuff (ignimbrite).
Till overlain by pumice and ash.

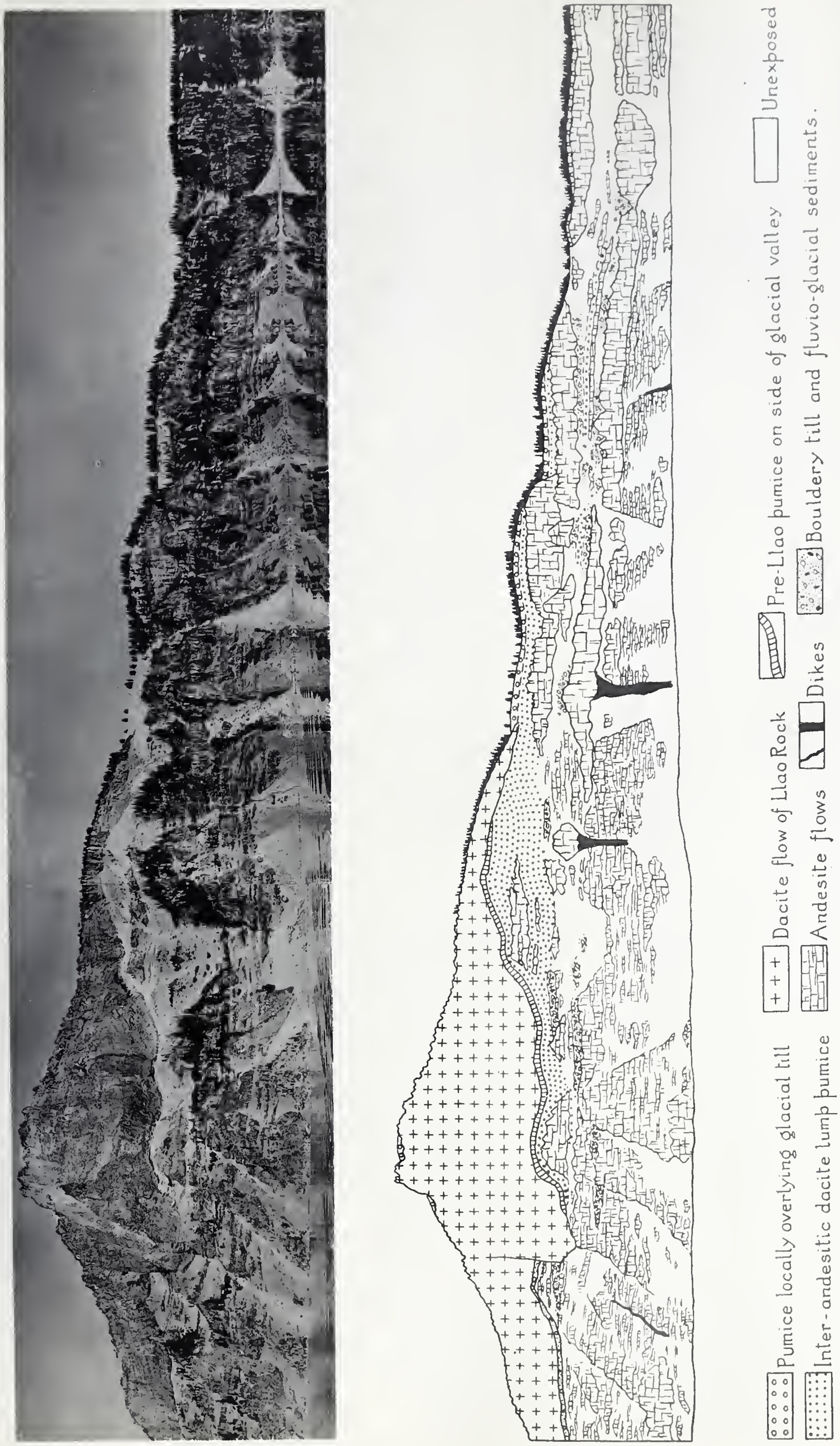
Panorama of the caldera wall: Palisades and Roundtop


N70°W
S70°E
Talus probably concealing pumice with interbeds of till and lenses of andesite
Thin andesites & interbedded pumice
Glacial Striae
Exposed till and fluvio-glacial beds
Same, but unexposed
Exposed flows of andesite
Coarse, bedded dacite pumice
The Cleetwood dacite flow and feeder
Welded dacite tuff (ignimbrite)
Topmost deposits, chiefly dacite pumice and crystal ash with lenses of glacial till and, above the S.E. wing of the Cleetwood flow, a layer of coarse lithic blocks. For details see text.

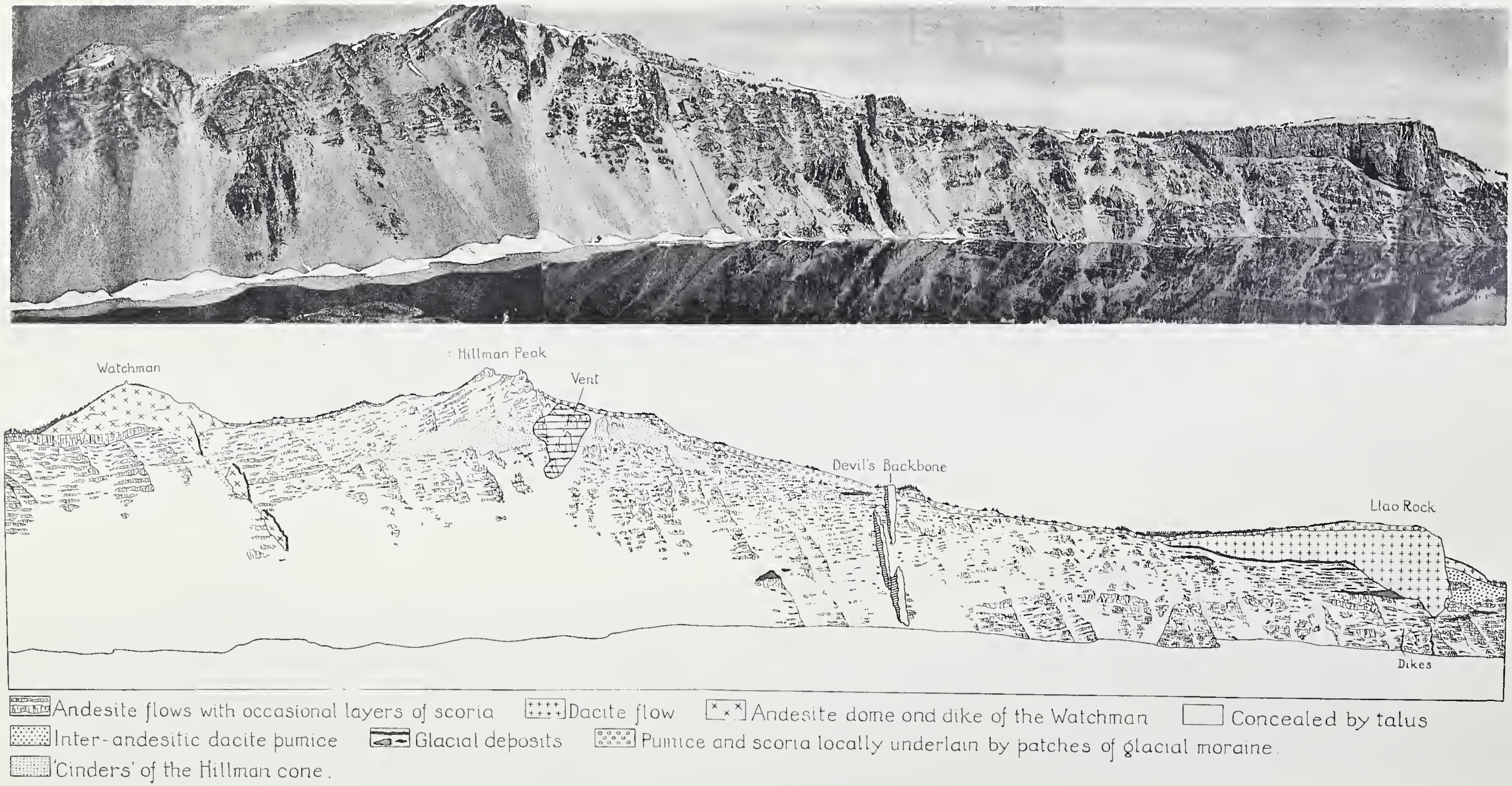
Panorama of the caldera wall: Cleetwood Cove



Panorama of the caldera wall: Pumice Point


Pumice locally overlying glacial till
Dacite flow of Llao Rock
Pre-Llao pumice on side of glacial valley
Unexposed
Inter-andesitic dacite lump pumice
Andesite flows
Dikes
Bouldery till and fluvio-glacial sediments.

Panorama of the caldera wall: Steel Bay


Watchman
Hillman Peak
Vent
Devil's Backbone
Llao Rock
Dikes
Andesite flows with occasional layers of scoria
Dacite flow
Andesite dome and dike of the Watchman
Concealed by talus
Inter-andesitic dacite pumice
Glacial deposits
Pumice and scoria locally underlain by patches of glacial moraine.
'Cinders' of the Hillman cone.

Panorama of the caldera wall: Watchman to Llao Rock. (Photographs by Elmer Aldrich.)

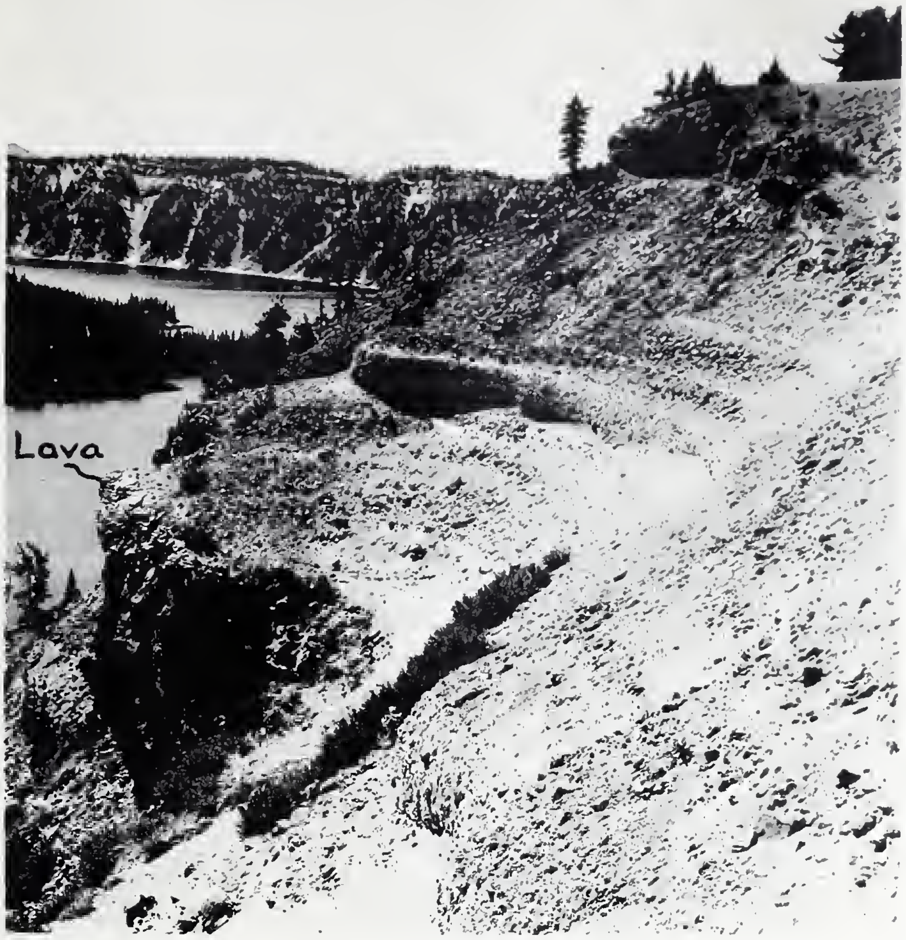


Fig. 1. Section on the caldera rim, 150 yards south of the Llao lava flow. Above the topmost lava lie 6 feet of lump pumice, then 30 feet of bouldery till, 7 feet of lump pumice with large lithic blocks (forming small cliff), 60 to 80 feet of bouldery till mixed with pumice, and finally the topmost pumice and scoria, products of the culminating eruptions of Mount Mazama. See also figure 7*a*.

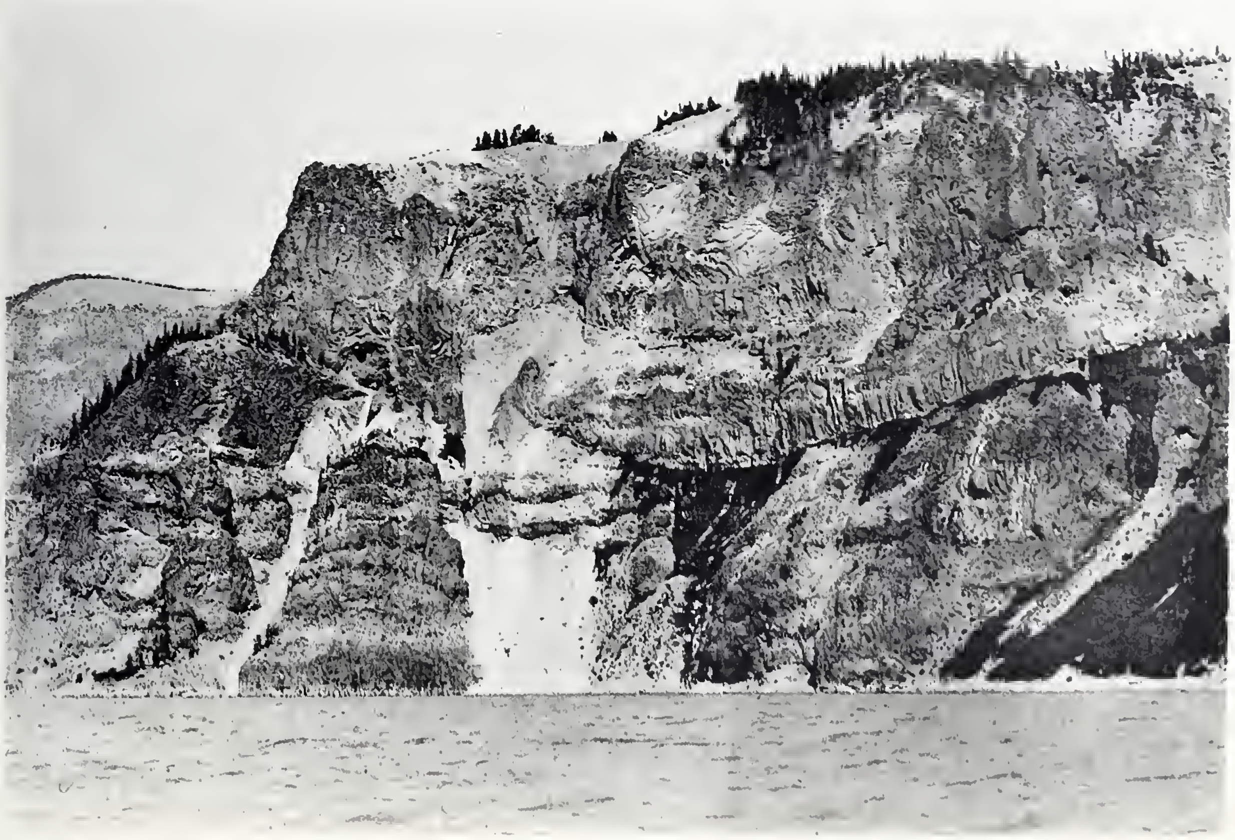
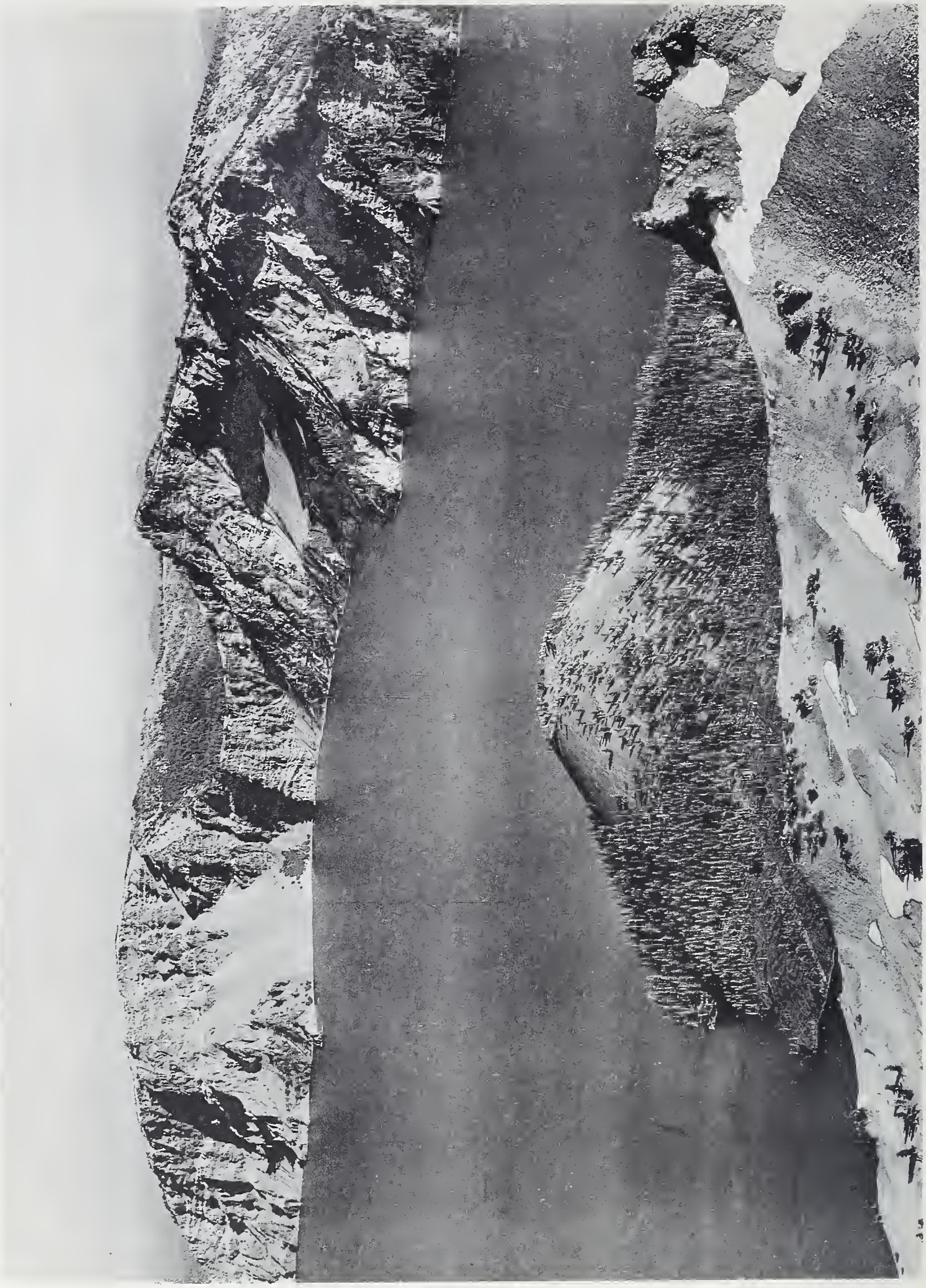


Fig. 2. Sentinel Rock. Upper part of wall formed by a thick flow of andesite, the vertical feeder of which is visible a little to the left of the center of the picture. Above the flow lie deposits of pumice and till. Beneath the flow lie two series of andesites, the upper resting in a broad valley carved by glaciers in the lower series. The dark streaks of vegetation indicate the seepage line between the two lava series, the water escaping from a thin stratum of glacial debris on the old valley floor. (Photograph by George Grant, National Park Service.)



The southeast wall of Crater Lake. From left to right: Dutton Cliff; Sun Notch; Applegate and Garfield peaks with the Chaski slide at their base; head of Munson Valley. Wizard Island in foreground. (Photograph by U. S. Army Air Corps.)

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